

**SEQUENTIAL DRY BATCH ANAEROBIC DIGESTION OF THE ORGANIC
FRACTION OF MUNICIPAL SOLID WASTE**

by

Nguyen Quang Huy

A thesis submitted in partial fulfillment of the requirements for the
degree of Master of Science in
Environmental Engineering and Management

Examination Committee: Prof. Chettiyappan Visvanathan (Chairperson)
Dr. Nguyen Thi Kim Oanh
Dr. Thammarat Kottatep

Nationality: Vietnamese
Previous Degree: Bachelor in Geology
Ha Noi University
Ho Chi Minh, Vietnam

Scholarship Donor: Vietnam Oil and Gas Corporation (Petrovietnam)
AIT Fellowship

Asian Institute of Technology
School of Environment, Resources and Development
Thailand
May 2008

Acknowledgements

Firstly, I would like to express my deepest gratitude to my advisor, Prof. C. Visvanathan, for his invaluable suggestion, advice and continuous encouragement extended throughout this research. No words can possibly express Prof. C. Visvanathan's deep enthusiastic guidance, patience.

I would like to express my profound gratitude to the committee members, Dr. Nguyen Thi Kim Oanh and Dr. Thammarat Koottatep for their helpful comments, constructive criticisms, and valuable discussions.

My special thanks go to Mrs. Radha Adhikari and all staff members in Environmental Engineering Program, Ms. Salaya., Ms Suchitra for supporting my throughout my stay in Asian Institute of Technology. I would like to thank the technician, Mr. Kum Tam for his extensive assistance during my research period.

Many thanks are due to the Asian Institute of Technology and the School of Environment, Resources and Development for providing the opportunity to receive the academic master training. I am grateful to the Petrovietnam Corporation for scholarship grant follow my master degree. My grateful appreciation is also expressed to Asian regional Research Program on Environmental Technology (ARRPET) Project "Sustainable Landfill Management in Asia" funded by Swedish International Development Co-operation Agency (SIDA) for partially funding for this research work.

I wish to thank my colleagues and friends in Environmental Engineering Program, who are always by my side for being helpful support and encouragement given during the study.

Finally, I wish to express my deep gratitude to my parents, wife and daughter.

Abstract

Solid waste is all the waste arising from human and animal activities that are solid and discarded as useless or unwanted. Integrated solid waste management includes waste collection, sorting, and treatment methods such as recycling, composting, incineration, anaerobic digestion and landfill. The problems associated with direct disposal in landfill are the possibility of ground and surface water contamination by the leachate, air pollution due to emission of landfill gases such as methane, carbon dioxide causes global warming. Aerobic and anaerobic treatment have been used as pre-treatment technologies before disposal. The anaerobic digestion generate energy in the form of methane and produces stable residue, which can be utilized as fertilizer.

This study aims to investigate the dry batch Bio-mechanization of Organic fraction of Municipal Solid Waste (OFMSW) as a pretreatment prior to landfill. In this study, batch dry fermentation of solid waste was used as a method of pretreatment of OFMSW prior to landfill. Furthermore the performance of the dry batch anaerobic digestion process of OFMSW was investigated in pilot scale experiments.

It found that circulation leachate reactor produced about 5 time more methane than the no circulation reactor, indicating that leachate circulation has a positive effect on methane recoveries. The specific methane yield as obtained with in three SEBAC reactors are 42, 230 and 100 L CH₄ /kg VS in 96 days and 45 days operation, respectively with the no circulation leachate reactor, direct circulation reactor and exchange leachate reactor. These values correspond to the 12%, 66%, 29 % process efficiency calculated based on the laboratory BMP assay. it also found that biogas production was strongly dependant on and very sensitive to the fluctuation of ambient temperature. The results of this experiment indicated that sequential batch operation investigated here overcomes the disadvantages of a batch reactor by successfully starting a digester by inoculation with leachate.

Table of Contents

Chapter	Title	Page
	Title page	i
	Acknowledgements	ii
	Abstract	iii
	Table of Contents	iv
	List of tables	
	List of Figures	vii
	List of Abbreviations	viii
1	Introduction	1
	1.1 Background	1
	1.2 Objectives of the study	2
	1.3 Scope of the study	2
2	Literature Review	3
	2.1 Introduction	3
	2.2 Integrated Solid Waste Management	3
	2.3 Solid Waste Generation in Asia	4
	2.4 Potential problems generation from MSW landfill	4
	2.5 Demand for pretreatment prior to landfill	5
	2.6 Potential Waste Generation Trend	6
	2.7 Biodegradability of organic waste component	7
	2.7.1 Biodegradability	7
	2.7.2 Ultimate biodegradability (Methane Potential) Bo	8
	2.8 Pretreatment Technologies	8
	2.9 Fundamentals of anaerobic digestion	9
	2.9.1 Anaerobic digestion	9
	2.9.2 The process of anaerobic digestion	10
	2.9.3 Hydrolysis	11
	2.9.4 Acetogenesis	12
	2.9.5 Methanogenesis	12
	2.10 Process Controlling Factors	12
	2.10.1 Nutrient Requirement	12
	2.10.2 Temperature	13
	2.10.3 pH	14
	2.10.4 Volatile Fatty Acids (VFA) concentration	14
	2.10.5 Particle size	14
	2.10.6 Ammonical-nitrogen	15
	2.10.7 Alkalinity	16
	2.11 Technology trends of anaerobic digestion	16
	2.11.1 Mesophilic versus thermophilic plants	17
	2.11.2 Low Solids Versus High Solids	18
	2.11.3 Batch and Continuous Processes	19
	2.11.4 Multi-phase versus single-phase digestion	20
	2.12 Co-digestion	20
	2.13 Post treatment	21
	2.13.1 Composting	21
	2.14 Sequential batch anaerobic digestion	22

	2.14.1 Leachate Recirculation	23
3	Methodology	25
	3.1 Introduction	25
	3.2 Biochemical Methane Potential (BMP) test	25
	A. Materials and equipment needed to conduct BMP test	25
	B. BMP test procedure	25
	3.3 Sequential batch anaerobic digestion (pilot scale)	26
	3.3.1 Feedstock preparation	26
	3.3.2 Reactor design and configuration	26
	3.3.3 Instruments/equipment need in SEBAC system	26
	3.3.4 Pilot-scale experimental runs	27
	3.3.5 Sequential operation	28
	3.4 Windrow composting	32
	3.5 Solid waste analysis	34
	3.6 Leachate characteristic analysis	35
	3.7 Biogas analysis	36
	3.8 Post-treatment of digested wastes	36
4	Results and Discussions	37
	4.1 Sequential Batch Anaerobic Digestion (SEBAC)	37
	A. Characteristics of feed and digested residue	38
	B. Biogas production	38
	C. Cumulative biogas production	40
	D. Biogas Composition	40
	E. pH	42
	F. TKN and Ammonia	43
	G. COD	45
	H. Specific cumulative methane production	46
	K. Overall SEBAC process assessment	47
	L. DOC	48
	M. BMP test	49
	4.2 Post treatment with windrow composting	50
5	Conclusion and Recommendations	54
	5.1 Conclusions	54
	5.2 Recommendations	55
	References	57
	Appendixes	66

List of Tables

Table	Title	Page
2.1	Typical constituents found in MSW landfill gas.	5
2.2	A solid waste composition in selected urban setting in Asia	6
2.3	Characteristics of SC-OFMSW collect in canteen	7
2.4	Biodegradable fraction of the organic constituents in MSW	8
2.5	Ultimate methane and biogas production of OFMSW	8
2.6	Possible unit processes, products and quality standard involved in anaerobic digestion plant for organic solids	9
2.7	Temperature range for bacteria	13
2.8	Effect of ammonia-nitrogen/ammonia in an anaerobic digester	15
2.9	Advantages and disadvantages of batch system	19
2.10	Advantages and disadvantages of one-stage dry system	20
2.11	Advantages and disadvantages of two-stage system	20
3.1	Solid waste analysis	36
3.2	Leachate characteristics analysis	36
3.3	Biogas analysis	36
3.4	Digested Analyses	37
4.1	Solid waste characterization	38
4.2	Overall SEBAC process assessments	47
4. 3	Unloading data for digesters	51
4.4	Quality of composting	53

List of Figures		
Figure	Title	Page
2.1	Composition of MSW in selected Asian countries	4
2.2	MSW compositions of selected Asian countries	7
2.3	Various methods of pre-treatment prior to landfill	9
2.4	A complex diagram for anaerobic digestion	11
2.5	Types of anaerobic digestion	17
2.6	Shares of mesophilic and thermophilic digestion systems	18
2.7	Market shares of single-step and multi-step plants (Baere et al. 2003)	18
2.8	Principal methanogenic reactions	22
2.9	Configuration of leachate recycles patterns in different batch system	23
3.1	Schematic representation of lab-scale (BMP test) procedure	26
3.2	Conceptual layout of this experiment	27
3.3	Anaerobic reactor design	28
3.4	Photograph of the reactors	29
3.5	Sequential anaerobic digestion systems	30
3.6	Schematic representations of the objectives of each experimental runs	31
3.7	The process in sequential operation	32
3.8	Composting unit at the site	33
3.9	Picture of Composting pile	34
4.1	Daily biogas production in R1, R2 and R4	38
4.3	Biogas composition in R1, R2 and R4	40
4.4	Variation of pH in R1, R2 and R4	42
4.5	TKN concentrations in R1, R2 and R4	43
4.6	Ammonia concentrations in R1, R2 and R4	44
4.7	Trend COD concentration in R1, R2 and R4	45
4.8	Specific methane production in R1, R2 and R4	46
4.9	Assessment process efficiency of R1, R2 and R4	47
4.10	Volatile solid reduction (%) of R1, R2 and R4	48
4.11	Trend DOC concentration in R1, R2 and R4	48
4.12	Cumulative daily biogas production in BMP test	49
4.13	Cumulative volume productions in lap scale	50
4.14	pH profile during the windrow composting pile	52
4.15	Temperature profile during the composting	53

List of Abbreviations

AD	Anaerobic Digestion
COD	Chemical Oxygen Demand
DOC	Dissolved Organic Carbon
GHGs	Greenhouse Gases
G _o	Ultimate Biogas Production
B _o	Ultimate biodegradability
Hac	Acetic acid
Hbu	Butyric acid
Hpr	Propionic acid
Hva	Valeric acid
MS-OFMSW	OFMSW from mechanical sorting
SC-OFMSW	OFMSW from separate collection
SS-OFMSW	OFMSW from source sorting
MSW	Municipal Solid Waste
NH ₄ -N	Ammonium Nitrogen
NmL	mL in STP
OFMSW	Organic Fraction of Municipal Solid Waste
SCOD	Soluble Chemical Oxygen Demand
SEBAC	Sequential Batch Anaerobic Composting
STP	Standard Temperature and Pressure
TCOD	Total Chemical Oxygen Demand
TDS	Total Dissolved Solids
TKN	Total Kjeldhal Nitrogen
TS	Total Solid
VFA	Volatile Fatty Acids
VS	Volatile Solid
WW	Wet Weight

Chapter 1

Introduction

1.1 Background

Solid waste is all the waste arising from human and animal activities that are solid and discarded as useless or unwanted. Integrated solid waste management includes waste collection, sorting, and treatment methods such as recycling, composting, incineration, anaerobic digestion and landfill. The landfills have been the most economical and environmentally acceptable method for the disposal of solid waste residue throughout the world; the rapid growth of population with unplanned urbanization plus industrialization increases the amount of the municipal solid waste.

The problems associated with direct disposal in landfill are the possibility of ground and surface water contamination by the leachate, air pollution due to emission of landfill gases such as methane, carbon dioxide causes global warming.

Increase environmental awareness and concern associated with direct landfill have stimulated biological treatment of organic waste before disposal. Aerobic and anaerobic treatment have been used as pre-treatment technologies before disposal. The anaerobic digestion generate energy in the form of methane and produces stable residue, which can be utilized as fertilizer.

Many types of reactors have been developed to treat wastes in an efficient, economical and environmentally acceptable way. The technologies vary from wet process to dry one, single-phase to multi-phase, from batch to continuous and variety of feedstock. Batch and high solid fermentation seems to be the most suitable method as pretreatment of Organic Fraction of Municipal Solid Wastes (OFMSW) prior to landfills with regard to developing country because of cost effective and simple in operation.

Anaerobic digestion has the advantage over composting due to positive energy balance. The Sequential Batch Anaerobic Composting (SEBAC) is a batch two-stage process. In first stage process, a coarsely-shredded feedstock is inoculated by recycling leachate from the anaerobically stabilized reactor. Volatile acid and other fermentation products generated during startup are removed from the fresh reactor to the stabilized reactor to convert to conversion to methane.

SEBAC of OFMSW involves two factors, which are leachate recirculation and phase separation in order to overcome the limitation of high-solid anaerobic digestion. SEBAC can operate well without addition of seeding materials (Chynoweth et al., 1992). However, application of anaerobic digestion process in developing countries is less practiced, due to the lack of appropriate treatment system configurations and the longer time required for the bio-stabilization of waste.

This study aims to investigate the dry batch Bio-mechanization of Organic fraction of Municipal Solid Waste (OFMSW) as a pretreatment prior to landfill.

In this study, batch dry fermentation of solid waste was used as a method of pretreatment of OFMSW prior to landfill. Furthermore the performance of the dry batch anaerobic digestion process of OFMSW was investigated in pilot scale experiments.

1.2 Objectives of the study

The specific objectives of this study are the followings:

- To investigate the performance of Sequential Batch Anaerobic Digestion (SBAD) process of organic fraction of solid waste in pilot scale experimental.
- To investigate performance of windrow composting system as a post-treatment technology suitable for complete stabilization of digested waste .

1.3 Scope of the study

- This study was implemented in two phases: first phase was the Biochemical Methane Potential (BMP) test that was conducted in laboratory scale, and the second phase was an anaerobic digestion experiment in pilot scale set-up in batch mode system.
- The study focused on pretreatment of organic fraction of municipal solid waste (OFMSW) collected from AIT campus.

Chapter 2

Literature Review

2.1 Introduction

Population growth, rapid urbanization and uncontrolled industrialization lead to increasing environment impacts in developing countries (DC). According to World Bank (1999), the urban population in Asia is 37% of the total population. The urban area generates 760,000 tons of municipal solid waste per day and is expected to rise up to 1.8 million tons in 2025. Most of the municipal solid waste (MSW) in DC is disposed into open dumpsite. The open dumping is creating serious environmental problems, harmful effect on human and animal health, economic and other welfare losses. The safe and reliable long-term disposal of solid waste residue is an important component of integrated solid waste management. Along with the increasing amount of MSW, pretreatment of solid waste prior to landfill become more and more important. Anaerobic digestion (AD) as pretreatment of organic fraction of municipal solid waste (OFMSW) prior to landfill can be considered as the preferable technology, an alternative to aerobic composting, and it also has many advantages over non-biological process. The composition of MSW stream in Asian cities shows 50% biodegradable organic fraction (Visvanathan et al., 2004). Therefore AD technology is promising to Asian countries because of the waste characteristics.

This chapter describes the theoretical reviews of fundamentals, operational conditions, limitations and performance parameters of anaerobic digestion process and discusses briefly the trend of MSW management in Asia

2.2 Integrated Solid Waste Management

Integrated solid waste management can be defined as the selection and application of suitable techniques, technologies, and management program to achieve specific waste management objective and goals (Tchobanoglous et al., 1993). The integrated solid waste management is composed of the following elements: source reduction, reuse, recycling, recovery, incineration, treatment and landfilling. The typical problem in Municipal Solid Waste Management (MSWM) of developing countries can be identified as; inadequate service coverage and operational inefficiencies of services, limited utilization of recycling activities, inadequate landfill capacity, and inadequate management of hazardous and healthcare waste (Visvanathan et al., 2004).

Municipal solid waste collection schemes of cities in the developing world generally serve only a limited part of the urban population. Recycling of organic waste material often contributing to more than 50% of the total waste amount and is still fairly limited. The organic fraction of MSW has great recovery potential. The recycling of OFMSW reduces costs of the disposal facilities, prolongs life span of landfill sites, and also reduces the environmental impacts.

2.3 Solid Waste Generation in Asia

The quantity and composition of MSW vary from site to site and are influenced by various parameters such as region, climate, recycling, reduction, use of in-sink disposal, collection frequency, season, and culture. The rapid economic growth in many Asian developing countries leads to a higher MSW generation. According to Visvanathan et al. (2004), the trend of MSW generation in the selected Asian countries shows that MSW in Asia is increasing with time. The MSW composition in some Asia countries is shown in figure 2.1.

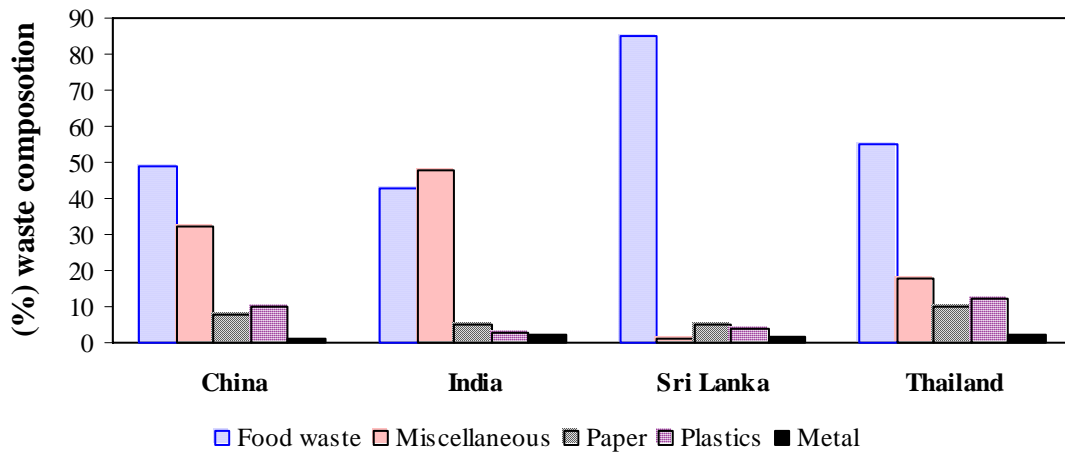
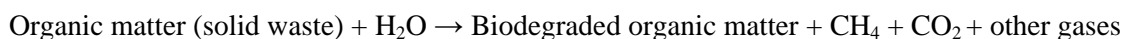


Figure 2.1 Composition of MSW in selected Asian countries (Visvanathan et al. 2004)

2.4 Potential problems generation from MSW landfill

Landfill is the physical facility, which is used for the disposal of residual solid wastes. Sanitary landfill refers to an engineered facility for the disposal of MSW and is designed and operated to minimize public health and environmental impacts. The landfill site can be conceptualized as a biochemical reactor with solid waste and water as the major inputs whereas the principal outputs are the landfill gas and leachate. The gases found in landfills include ammonia (NH_3), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4). The Table 2.1 presents the typical constituents found in MSW landfill gas. Vieitez et al. (2000) showed that biotransformation or natural degradation of landfill materials occurs in a very slow process and may require several decades for completion. They also added that anaerobic fermentation in landfills extends for periods of 20-40 years and it took decades for the methane content to reach 50%. Therefore methane and carbon dioxide are the main products resulting from the degradation of organic matter in the landfill. The general chemical reaction for the anaerobic decomposition of solid waste can be written as the following equation:



Both CO_2 and CH_4 are important greenhouse gases. Methane contributes to global warming potential of about 25 times greater than carbon dioxide. In recent years, methane has been recognized as a significant greenhouse gas (Rodhe, 1990).

Table 2.1 Typical constituents found in MSW landfill gas.

Component	Percent (dry volume basis)
Methane	45-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0.1-1
Sulfides	0-0.1
Ammonia	0.1-1
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

Source: Techobanoglous et al. (1993)

Leachate consists of dissolved and suspended material associated with wastes discharged from the landfill and many byproducts of chemical and biological activities occurring as the solid waste degrades. Dissolved organic matter, inorganic macro-compounds (calcium, magnesium, sodium, potassium etc.), heavy metals (cadmium, copper, chromium, lead), and xeno-biotic organic compounds (aromatic hydrocarbons, phenols, etc). It has been estimated that groundwater pollution originating from landfills may be at risk even after several centuries (Ludwig et al., 2003).

2.5 Demand for pretreatment prior to landfill

Landfill plays an important role in integrated solid waste management. The current landfilling situation in Asia countries is causing various problems related to cultural and climatic differences, along with the waste composition and improper waste management. The significant environmental impacts of landfill create detrimental effects to the air, water, and soil environment. The uncontrolled production of landfill gas that consists of methane, carbon dioxide and traces of non-methane volatile organic carbons and halocarbons lead to ozone depletion and eventually contribute to global warming effect. The unregulated formation of leachate generation by percolating rain water and contain runoff of organic and inorganic compounds results in contamination of soil, surface, and groundwater. This may be exacerbated by the fact that leachate generated at any point in time is a mixture of leachates derived from solid waste at different ages. All these significant emissions were associated with landfills. Moreover, the issue related to aesthetic nuisance is mainly due to foul odour, noise, dust, appearance, and susceptibility to explosion/fire hazards. Nevertheless, the risk in landfill stability was one of the major geotechnical tasks in landfill design and operation and has been a problem for years (Kosch and Ziehmman, 2004). Heterogeneous waste composition obstacles in determining waste strength parameters and insufficient knowledge on the principles of waste management is resulting in considerable uncertainties in landfill stability (Visvanathan, 2005).

Landfilling is considered to be the most cost-effective method of solid waste disposal in developing countries if sufficient land is available. Significant problem with landfills is simply due to their large are requirements, the expense on valuable area they occupy, and the landfill criteria which are mounting with the urban population growth and increased waste generation. The existing landfill sites are nearly exhausted and new landfill sites are hardly available because of shortage of utilizable land. The mechanical-biological pre-treatment or simple composting has been suggested as a feasible option for improving the

landfill performance in the tropical region. Various methods of pre-treatment prior to landfill are described in figure 2.3. Typical benefits of anaerobic process are listed as the followings (Visvanathan, 2004) :

- Landfill area/volume reduction up to 40%
- Increase of stability of landfill due to the reduction of biodegradability of solid waste.
- Prevention of hazardous waste to the site as mechanical sorting is followed by biological treatment.
- Maximization of recycling and reuse
- Prevention of aesthetic nuisance

2.6 Potential Waste Generation Trend

Municipal solid waste (MSW) is generated from households, offices, hotels, shops, schools and other institutions. The major components are food waste, paper, plastic, rags, metal and glass, although demolition and construction debris is often included in collected waste, as are small quantities of hazardous waste, such as electric light bulbs, batteries, automotive parts and discarded medicines and chemicals.

Table 2.2 A solid waste composition in selected urban setting in Asia

City	Waste categories (average percentage wet weight)						
	Bio-degradable	Paper	Plastic	Glass	Metal	Textile & leather	Iner (ash each) & others
Indonesia	74	10	8	3	2	2	2
Dahaka	70	4.3	4.7	0.3	0.1	4.6	16
Kathmandu	68.1	8.8	11.4	1.6	0.9	3.9	5.3
Bangkok	53	9	19	3	1	7	8
Ha Noi	50.1	4.2	5.5	-	2.5	-	37.7
Manila	49	19	17	-	6	-	9
India	42	6	4	2	2	4	40
Karachi	39	10	7	2	1	9	32

Source: Zubbügg (2002)

According to Visvanathan et al. (2004), major portion of the MSW generated in most Asian countries is dominated by biodegradable organic fractions composed of food wastes, yard wastes and mixed paper. Figure 2.2 and Table 2.2 clearly illustrate that food wastes dominates over the major portion of the waste generated in most developing countries in Asia like China, India, Sri Lanka, Thailand and average characteristics in selected urban setting in Asia.

Furthermore, OFMSW is the general term for the MSW that are usually obtained in three pathways: the mechanical selection from the unsorted waste, the separate collection, and source sorting. Corresponding to these, there are three types of OFMSW:

- Mechanical sorting (MS-OFMSW)

- Separate collection (SC-OFMSW) and
- Source sorting (SS-OFMSW)

The OFMSW from separate collection can be split into two categories the organic fraction coming from markets, canteens, restaurants, etc and the organic fraction coming from domestic source sorting. Typical content in SC-OFMSW substrate had TS content of 25% with volatile solid of 80%. Table 2.3 reports the data regarding the SC-OFMSW from canteen.

2.7 Biodegradability of organic waste component

The most important biological characteristic of the organic fraction of MSW is that almost all of the organic components can be converted biologically to gases and relatively inert organic and inorganic solids. Two types of biodegradability can be discerned, the “ultimate” biodegradability and biodegradability.

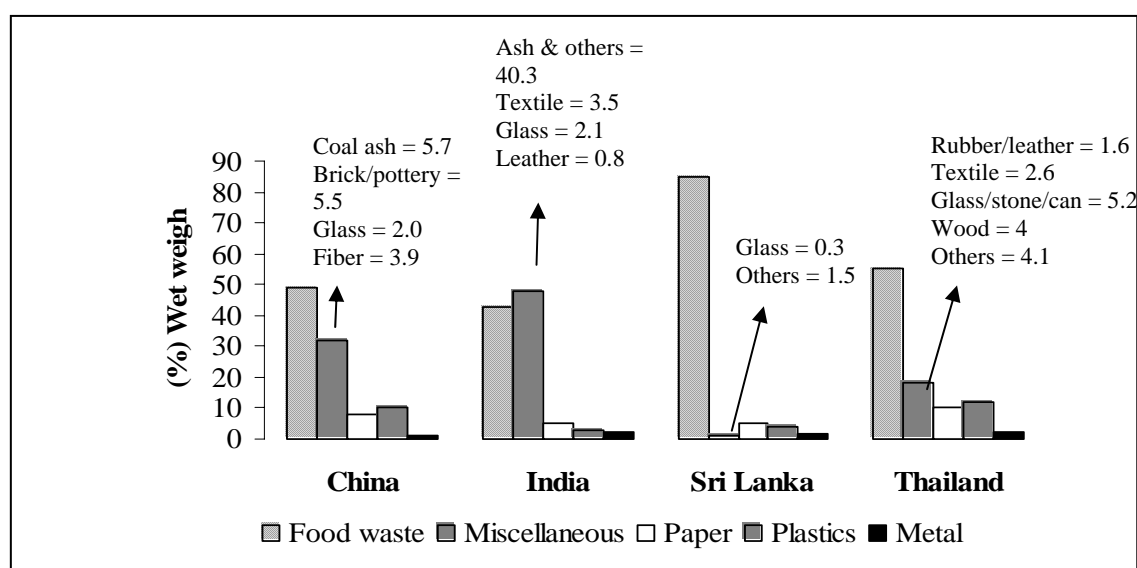


Figure 2.2 MSW compositions of selected Asian countries (Visvanathan et al., 2004)

Table 2.3 Characteristics of SC-OFMSW collect in canteen

Parameter	Range	Typical value
TS %	21.4	25.6
TVS (TS %)	91.3 – 99.7	96.5
TCOD(gO ₂ /g TS)	1.2 -1.3	1.2
TKN (% TS)	2.6 -3.7	3.2
Total P (% TS)	0.13 – 0.28	0.2

Source: Cecchi et al. (1997)

2.7.1 Biodegradability

Biodegradable fraction (BF) of waste is related to the volatile solid content (VS) which is determined by ignition at 550°C. Volatile solid (VS) or Level of Ignition (LOI) is usually used for description of solid waste characteristics. However, the use of VS in describing

the biodegradability is misleading as some of the organic constituents are highly volatile but low in biodegradability (e.g., new sprint and certain plant trimmings). Waste with high lignin content such as newsprint are significantly less biodegradable than the other organic compounds found in MSW.

Table 2.4 Biodegradable fraction of the organic constituents in MSW

Organic waste component	Biodegradable fraction, %VS
Food waste	0.82
Newspaper	0.22
Office paper	0.82
Cardboard	0.47
Yard waste	0.72

Source: Tchobanoglous et al., (1993)

2.7.2 Ultimate biodegradability (Methane Potential) Bo

Chanedler et al (1980) proposed that biodegradability of particulate organic substrate could be predicted based on its lignin content. Tong et al. (1990), however, showed that the biodegradability also depends on the structure of the lignocellulose complex. Cellulose is readily degradable but becomes less degradable or even refractory when incorporated into the lignocellulose complex. Typical biodegradable fractions of some organic constituents in MSW are presents in Table 2.4.

Ultimate methane yield represents the biological characteristic of the substrate in terms of their response to the anaerobic digestion process. Ultimate methane yield of the waste is maximum amount of biogas that is produced for a given amount of volatile solids (VS). Therefore it is conducted in the prevalence of optimal condition. This shows the biodegradability of the substrate. For different wastes, even with same volatile solid and biodegradation fraction Methane Potential are different since this parameter taken into account the origin of the waste.

Range of ultimate gas productions can be evaluated, both in terms of methane and biogas production. Considering a methane percentage of 57-69% (Polprasert, 1996), these values are reported in Table 2.5.

Table 2.5 Ultimate methane and biogas production of OFMSW

Substrate	MS-OFMSW	SC-OFMSW	SS-OFMSW
B _o , m ³ CH ₄ /kg TVS	0.16-0.37	0.45-0.49	0.37-0.40
G _o , m ³ /kg TVS	0.29-0.66	0.81-0.89	0.67-0.72

Source: Mata Alvarez et al. (2003)

Go: ultimate biogas production

Bo: Ultimate biodegradability (Methane Potential)

2.8 Pretreatment Technologies

There are varieties of pretreatment processes that are practiced on the characteristics of the incoming waste and the effects they have on AD. This is of particular importance to improve the performance of digesters treating solid wastes. There is an obvious link between successful pretreatment and improved yields. By means of efficient pretreatment, the solids particle can be made more accessible for the anaerobic microbial consortium, optimizing the methanogenic potential of the solid waste to be treated. The most promising

pre-treatment process is source separation. This provides an immediate clean waste stream that will have some residual plastics with the greater portion of the waste being clean and ready to digest, pretreatment of organic fraction of MSW prior to landfill is illustrated in figure 2.3.

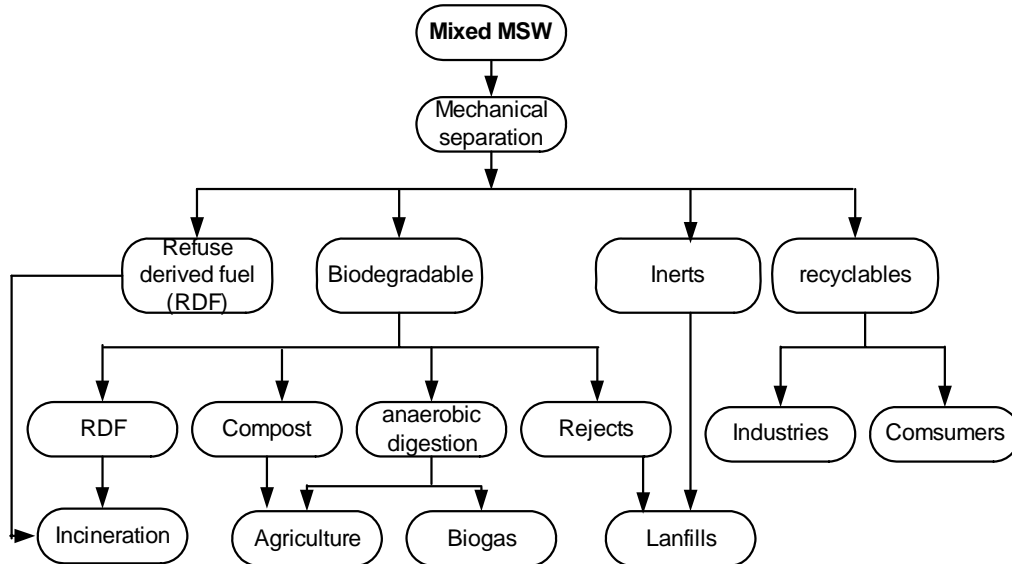


Figure 2.3 Various methods of pre-treatment prior to landfill

Separation technologies for metals, glass, and plastic are usually necessary and similar to those used in material recovery facilities. These pretreatments can be biological, mechanical, thermo-chemical or physico-chemical. There are several ways in which can be accomplished. Table 2.6 shows the typical pre-treatment technologies, digestion process and post treatment technologies.

2.9 Fundamentals of anaerobic digestion

2.9.1 Anaerobic digestion

The anaerobic digestion is the biological process in the absence of oxygen. That decomposes organic matter. The main product is biogas which is a mixture of approximately 65% methane and 35% carbon dioxide-along with a reduced amount of a bacterial biomass (Mata-Alvarez et al, 2003). Figure 2.3 shows the basic steps in anaerobic digestion.

OFMSW is a complex substrate and requires more complex metabolic pathway to be degraded as it involves complex series of metabolic reaction before final conversion to methane. Anaerobic digestion of organic fraction of MSW as pretreatment prior to landfill especially involves three main phases as combined process: pretreatment, anaerobic digestion process and post treatment.

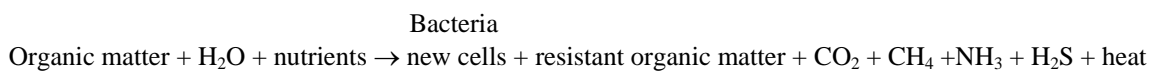
Table 2.6 Possible unit processes, products and quality standard involved in anaerobic digestion plant for organic solids

Unit process	Reusable products	Standard or criteria
<i>Pre-treatment</i>		
- Magnetic separation	-Ferrous metals	-Organic impurities
- Size reduction (drum or shredder)	-Heavy inert reused as construction material	-Combination of paper, cardboard and bags
- Pulping with gravity separation		-Germs die off
- Drum screening		
- Pasteurization	-Coarse fraction, plastics	
<i>Digestion</i>		
- Hydrolysis	- Biogas	-Nitrogen and sulfur contents
- Methanogenesis	-Electricity	-150-300 kW.h _{electricity} /ton
- Biogas utilization		
<i>Post-treatment</i>		
- Mechanical dewatering		-Load on water treatment
- Aerobic stabilization or biological dewatering	-Compost	-Soil amendments
- Water treatment	-Water	- Disposal regulation
- Biological dewatering	- Compost	- Soil amendments
- Wet separation	-Sand, fiber (peat), sludge	-Disposal regulations
		-Organic impurities

Source: Vanderviviere et al. (2002)

2.9.2 The process of anaerobic digestion

In the anaerobic decomposition of wastes, various anaerobic organisms work together to bring about the conversion of organic portion of the wastes to stable end products. The general anaerobic transformation of solid waste can be described by the following equation.



The biological conversion of the organic fraction of MSW under anaerobic conditions is thought to occur in four steps as shown in Figure 2.4.

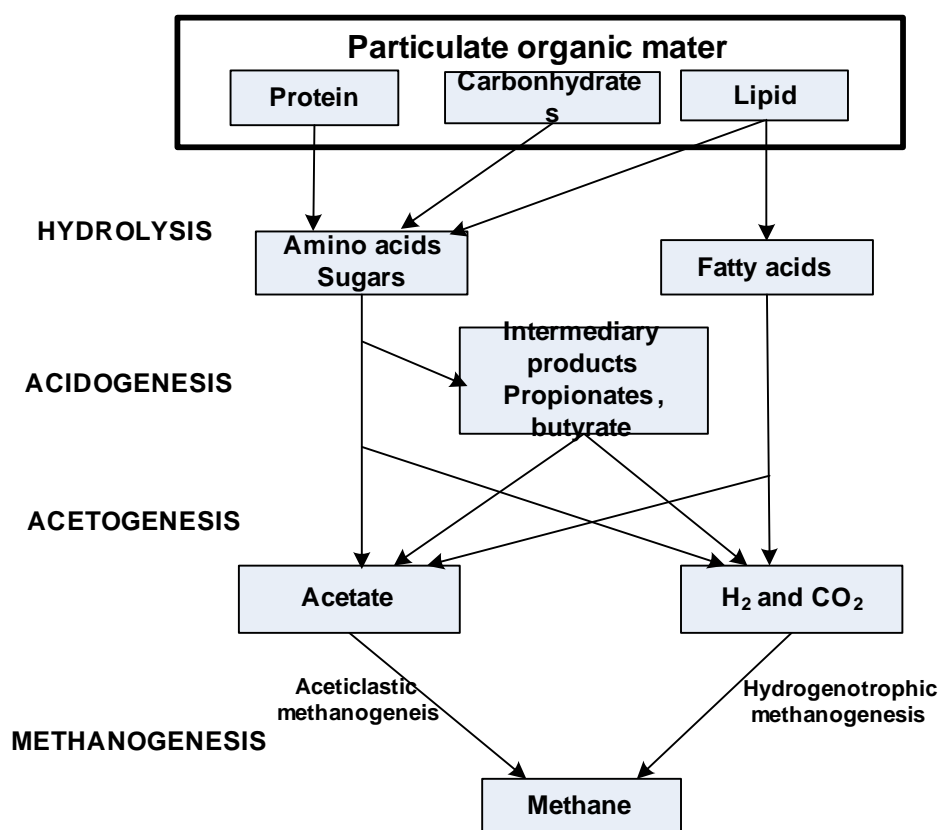
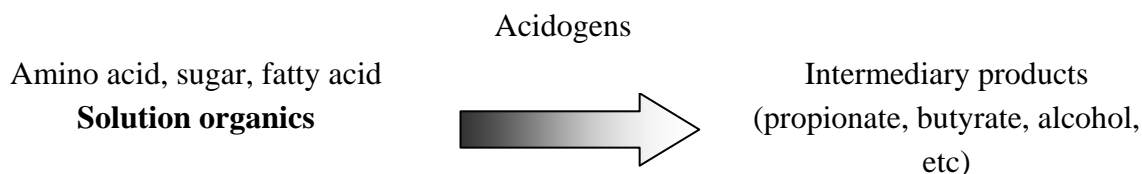


Figure 2.4 A complex diagram for anaerobic digestion considering four simultaneous processes (Mata-Alvarez et al., 2003)

2.9.3 Hydrolysis

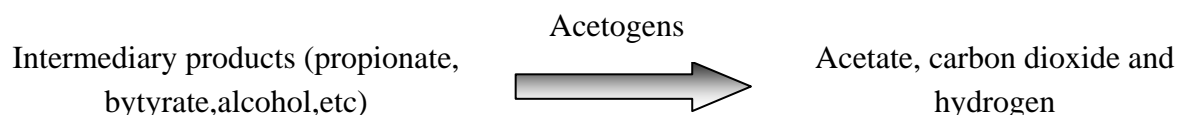
The first step in anaerobic biodegradation is the conversion of the complex waste (including particulate and soluble polymer) into soluble products by enzymatic hydrolysis. The stage will be accomplished by the presence of hydrolytic bacteria, which secretes extra cellular enzymes breaking down complex substrates.

Hydrolysis reaction in this stage will convert (1) protein into amino acids, (2) carbohydrate into simple sugars, and (3) fat into long-chain fatty acids. These simple products are organic monomers, which will be further fermented, in the next stage of the process. Liquefaction of cellulose and other complex compounds to simple monomers can be the rate-limiting step in anaerobic digestion. The hydrolysis rate is dependent on substrate and bacterial concentrations, as well as on environmental factors such as pH and temperature.



2.9.4 Acetogenesis

The monomers resulted from hydrolysis will be converted to various intermediates, mainly Volatile Fatty Acid (VFA) such as acetic, propionic, butyric and valeric acids, H₂ and CO₂. Ammonia is also produced by the degradation of amino acids. The group of microorganisms responsible for this biological conversion is described as non-methanogenic and consists of facultative and obligate anaerobic bacteria that are often identified in the literature as “acidogens” or “acid formers”.



2.9.5 Methanogenesis

Methane is the only reaction product that is not a reactant in the whole process and can, therefore, be considered as an end product. Two processes generate it. The bacteria responsible for these conversions are strict anaerobes, called methanogens, and are identified in the literature as “methanogens” or “methane former”. The methanogens can be classified into two groups following two processes to produce methane. Acetoclastic bacteria utilize acetic acid to produce methane whereas hydrogen-utilizing methanogenic bacteria convert H₂ and CO₂ to methane



The first mechanisms account for producing mostly CH₄ in the overall process. Methanogens have very slow growth rates. As a result, their metabolism is usually considered as rate-limiting in the anaerobic treatment of anaerobic organic waste. Waste stabilization in anaerobic digestion is accomplished when methane and carbon dioxide are produced. Methane gas is insoluble, and its departure from a landfill or solution represents actual waste stabilization.

The methane formation is very important in anaerobic digestion because it can produce methane gas and regulates the pH by converting VFA into bicarbonate. Among several kinds of methanogens, it is suggested that the bacteria utilizing propionic and acetic acids are the most important (McCarty cited in Pfeffer, 1979).

2.10 Process Controlling Factors

2.10.1 Nutrient Requirement

Nutrients are one of the most important environmental factors in biological process and anaerobic digestion in particular. Nutrient needs for in anaerobic biological treatment process may be grouped as macronutrients and micronutrients. Macronutrients are nitrogen and phosphorus that are required in relatively large quantities by all bacteria. Micronutrients are (K, Mg, Ca, Fe, Na, Cl, Zn, Mn, Mo.) that are required in relatively small quantities by most bacteria. The inorganic nutrients critical in the conversion of acetate to methane.

The amount of nitrogen and the amount of phosphorus that must be available in the digester can be determined from the quantity of substrate or COD of the digester feed solid waste. Nutrient requirement for anaerobic digester vary greatly at different organic loading rates. Generally, COD: N: P of 1000:7:1 and 350:7:1 have been used for high strength waste and low loading (Garadi, 2003). Ratio value of C/N of has at 25:1 (Polprasert, 1996) that suggested for optimal gas production.

2.10.2 Temperature

Temperature has an important effect on the survival and growth of microorganism. According to the temperature range in which they function best, bacteria may be classified as psychrophilic, mesophilic, thermophilic and hyperthermophiles (the table 2.7 show the optimum temperature ranges for the growth of methane-forming bacteria).

Most methane-forming bacteria are active in two temperature range . These range are the mesophilic range from 30 to 35°C and the thermophilic range from 50-60°C. At the temperature between 40°C and 50°C, methane forming bacteria are inhibited (Garadi, 2003). Although methane production can occur over a wide range of temperatures, anaerobic digestion of methane production municipal solid waste is performed in mesophilic range, with optimum temperature of approximate 35°C. Whenever digester temperature fall below 32°C, close attention should be paid to the volatile acid-to-alkalinity ratio. Volatile acid formation continues at depressed temperatures, but methane production proceeds slowly. Volatile acid production can continue at a rapid rate as low as 21°C, whereas methane production is essentially nonexistent. Therefore the temperature of 32°C is the minimum temperature that should be maintained, and 35°C is the preferred temperature.

The rate of anaerobic digestion of solid waste and methane production is proportional to digester temperature, that higher the temperature the greater the destruction rate of volatile solids and the production of methane. The rate of anaerobic digestion of solid waste and methane production is consider faster in thermophilic digester than mesophilic digesters 25% to 50% (Garadi, 2003). But thermophilic anaerobes are very sensitive to rapid changes in temperature, the fluctuation in digester temperature should be as small, that is < 1°C per day. Mesophiles is 2-3°C per day.

The temperature influences not only methane-forming bacteria but also volatile acid forimg bacteria. Therefore, fluctuations in temperature may be advantageous to certain groups and disadvantageous to other groups. Past studied (Garadi, 2003) showed that a fluctuations in temperature changed 10°C would stop methane production while volatile acid production would increase.

Table 2.7 Temperature range for bacteria

Bacteria group	Temperature range, °C
Psychrophiles	5-25
Mesophiles	30-35
Thermophiles	50-60
Hyperthermophiles	>65

Source: Garadi (2003)

The effect of temperature on hydrolysis of particulate waste is not very large. Hydrolytic bacteria are not as sensitive to temperature change as the acetate forming and methane forming bacteria. Temperature affects biological activity. This effect is due to mostly the impact of temperature on enzymatic activity or reactions therefore increase in temperature result in more enzymatic activity whereas decreases in temperature result in less enzymatic activity because of impact of temperature on enzymatic activity, the solid retention time within digesters should increase with decreasing temperature .

2.10.3 pH

The pH value gives some information about the stability of the medium since its variation depends on the buffer capacity of the medium itself. The pH is an indicator of a complex equilibrium system where several chemical species are involved. They are bicarbonate concentration (HCO_3), volatile fatty acid (VFA) and ammonia ($\text{NH}_4\text{-N}$). Variations in pH are related to variations of these species. The pH and VFA are linked to each other but their relation depends on the waste composition which may differ from the type of waste and the environmental conditions of anaerobic digestion process. The growth of anaerobic microorganisms like methanogens can be inhibited by acidic condition because they are sensitive to acid concentration. Moreover, pH plays a major role in anaerobic biodegradation in which pH influences the activity of microorganisms. An optimum pH value for anaerobic digestion lies between 6.4 and 7.2 (Chugh et al., 1999).

During digestion the two processes such as acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and acetogenesis occurs rapidly in batch reactor. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5.

If the pH in an anaerobic reactor should decrease, the feeding to the reactor should be stopped and should increase the buffering capacity e.g. through adding calcium carbonate, sodium bicarbonate or sodium hydroxide. This is, of course, an expensive way of dealing with the problem, and a better way is to avoid the accumulation of VFAs by suitable process design and operation.

2.10.4 Volatile Fatty Acids (VFA) concentration

The VFA are major and important intermediary compounds of the anaerobic digestion of organic matter. Vieitez and Ghosh (1999) showed that fermentative reactions stopped at a VFA concentration of 13,000 mg/L accompanied by a low pH of 5. The limiting step in anaerobic digestion is hydrolysis and usually it is inhibited by high propionate concentration. According to Anderson et al. (1982), unionized acids (free acids) was the major limiting factor and was considered as inhibitory to the activity of bacteria. .

It was suggested by Vavilin et al. (2003) that diffusion and advection of VFA inhibiting both polymer hydrolysis and methanogenesis. Increases of initial hydrolysis rate above a critical value cause an inhibition, firstly methanogenesis and then hydrolysis

2.10.5 Particle size

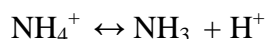
According to Sanders et al. (2000), the hydrolysis rate was directly related to the amount of substrate, and the surface area of the particulate substrate was the key factor for the hydrolysis process. This idea was supported by Veeken and Hammelers (1999a, b) that the rate of hydrolysis of particulate organic matter is determined by the adsorption of hydrolytic enzymes to the biodegradable surface sites and an increase in biodegradability

results in an increase in adsorption sites for enzymes. Thus, reduced particle size could increase hydrolysis rate and shorten digestion time.

2.10.6 Ammonical-nitrogen

Ammonia- nitrogen ($\text{NH}_4^+ - \text{N}$) or ammonium ions (NH_4^+), a reduced form of nitrogen, may be transferred to an anaerobic digester or may be produced during the anaerobic degradation of organic nitrogen compound such as amino acids and proteins. Reduced nitrogen exit in two forms, the Ammonia- nitrogen and free or unionized ammonia (NH_3). The effect of Ammonia- nitrogen/ ammonia in the anaerobic digester is positive and negative (the table 2.8 shows the effect of Ammonia- nitrogen/ ammonia in the anaerobic digester). Ammonium ions are used by bacteria in the anaerobic digester as a nutrient source for nitrogen. Free ammonia is toxic.

According to Garardi (2003) the amount of each form of reduced nitrogen in an anaerobic digester is determined by the digester pH at 9.3. With increasing pH, the amount of free ammonia increase. Whereas with decrease in pH, the amount of ammonium ion increase. At pH 7, free ammonia accounts for approximately 0.5% of the total reduced nitrogen.



Free ammonia is toxic to methane-forming bacteria. The toxic effect of ammonia as well as cyanide and hydrogen sulfide are determined by digester pH. All are toxic in their undissociated (unionized) form i.e. NH_3 , HCN and H_2S . There is direct effect of pH on ammonia and with increasing pH ammonia is produced in large quantities. The pH effect on cyanide and hydrogen sulfide in large quantities. Although methane-forming bacteria can acclimate to free ammonia, unacclimatized methane-forming bacteria can be at free ammonia concentration higher than 50 mg/L.

Table 2.8 Effect of ammonia-nitrogen/ammonia in an anaerobic digester

Effect of ammonia-nitrogen (NH_4^+)/Dissolved (NH_3), N	Effect
50-200 mg/L	Beneficial
200-1000 mg/L	No adverse effect
1500-3000 mg/L	Inhibitory at pH>7

Source: Garadi (2003)

Concentration of ammonia higher than 50mg/l can be tolerated by methane-forming bacteria, if the bacteria have been acclimatized. If the bacteria can not be acclimatized to free ammonia, digester pH can be decrease or digester feed sludge can be diluted to prevent ammonia toxicity.

The toxic effect of free ammonia may be confined to methane-forming bacteria and the precise concentration at which free ammonia is toxic remains uncertain. However, anaerobic digester with free ammonia is toxic uncertain. However, anaerobic digester with acclimatized population of methane forming bacteria can tolerate several hundred milligram per liter of free ammonia. Ammonia concentration higher than 1500 mg/L at higher pH may result in digester failure. At concentration above 3000mg/L, free ammonia become toxic enough to cause digester failure.

A shock loading of free ammonia causes a rapid and large accumulation of volatile acids and a rapid and significant drop in pH. Besides volatile acid accumulation, loss of alkalinity, drop in pH and a decrease in methane production are indicative of ammonia toxicity. A common cause of digester failure is the presence of an unacclimatized population of methane-forming bacteria which should be acclimated to increasing concentration of ammonia.

2.10.7 Alkalinity

Alkalinity is the acid-neutralizing capacity of a medium i.e. the capacity to resist changes in pH caused by the increase of acids in the medium. It results from the presence of hydroxides, sodium potassium or ammonia. Typical values of alkalinity in anaerobic digesters are in the range 2000-4000 mg CaCO₃/L.

Alkalinity is the result of the release of amino groups (-NH₂) and production of ammonia (NH₃) as the proteinaceous wastes are degraded. Alkalinity in an anaerobic digester also is derived from the degradation of organic-nitrogen compounds, such as amino acid and proteins, and the production of carbon dioxide from the degradation of organic compounds. When amino acids and proteins are degraded, amino groups (-NH₂) are released and alkalinity is produced. When amino groups are released, ammonia is produced. The ammonia dissolves in water along with carbon dioxide to form ammonia bicarbonate (NH₄HCO₃).



The alkalinity is present primarily in the form of bicarbonates that are in equilibrium with carbon dioxide in the biogas at given pH. Significant changes in alkalinity or pH are introduced in anaerobic digester by substrate feed or the production of acidic and alkalinity compounds during the degradation of organic compounds in the digester such as organic acids and ammonium ions respectively.

2.11 Technology trends of anaerobic digestion

A wide variety of engineered systems have been specifically developed for the rapid “in vessel” digestion of the OFMSW and other types of organic wastes. Each has its own special benefits and constraints. A general overview of the basic principles is given in Figure 2.5, which can be applied to either wet or dry fermentation techniques.

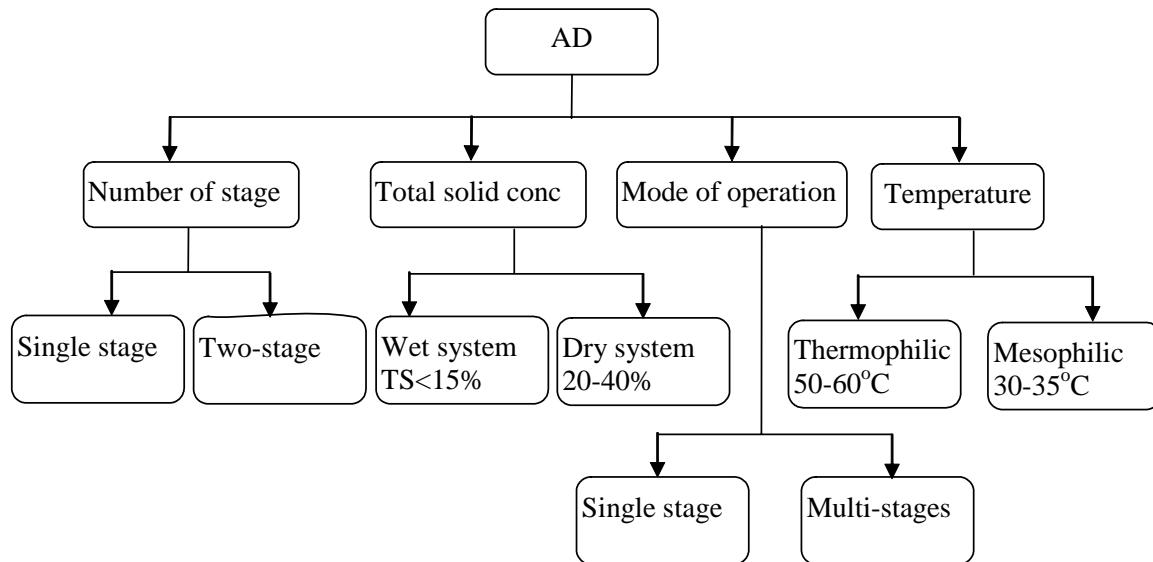


Figure 2.5 Types of anaerobic digestion

2.11.1 Mesophilic versus thermophilic plants

The anaerobic digestion may be performed at thermophilic (typically 50-60°C) or mesophilic temperatures (typically 30-35°C). The rate of anaerobic digestion of MSW and methane production is considerably faster in thermophilic digester than in mesophilic digester. In the first stage, the process hydrolyzes organics with concomitant production of methane at a faster (Gerardi, 2003). This allows higher loading rates and is advantageous for treating MSW because of increased hydrolysis rates.

The optimum temperature of digestion may vary depending on feedstock composition and type of digester but in most anaerobic digestion processes. Both mesophilic and thermophilic technologies for anaerobic digestion are proven systems.

The capacity of mesophilic operation increased from 180,000 ton to 1,800,000 during 1990 through 2004, while thermophilic capacity increased from 20,000 tons during 1992 thorough 2004 to 600,000 tons (Figure 2.6). Mesophilic plants are considered as a pioneering technology. The evolution of thermophilic plants increases with time. Nowadays, there are still mesophilic plants.

Monnet (2003) showed that the thermophilic digesters are more efficient in terms of retention time, loading rate and nominally gas production. However, the disadvantages of thermophilic system are more expensive technologies, greater energy input and a higher degree of operation and monitoring. There is an energy balance argument supporting the use of the energy produced to maintain thermophilic operating temperatures.

The vast majority of digestion, especially of OFMSW, is carried out in these two temperature ranges. Baere (2003) indicates that in the year 2000, of the more than 1 million tonnes of installed capacity for digestion of the OFMSW, more than 600,000 tonnes was in the mesophilic range with thermophilic accounting for just less than 400,000 tonnes. The development of thermophilic digestion capacity has, however, lagged the

mesophilic, and over the 1996-2000 period, figure 2.6 suggest that mesophilic capacity has increased by only slightly more than thermophilic.

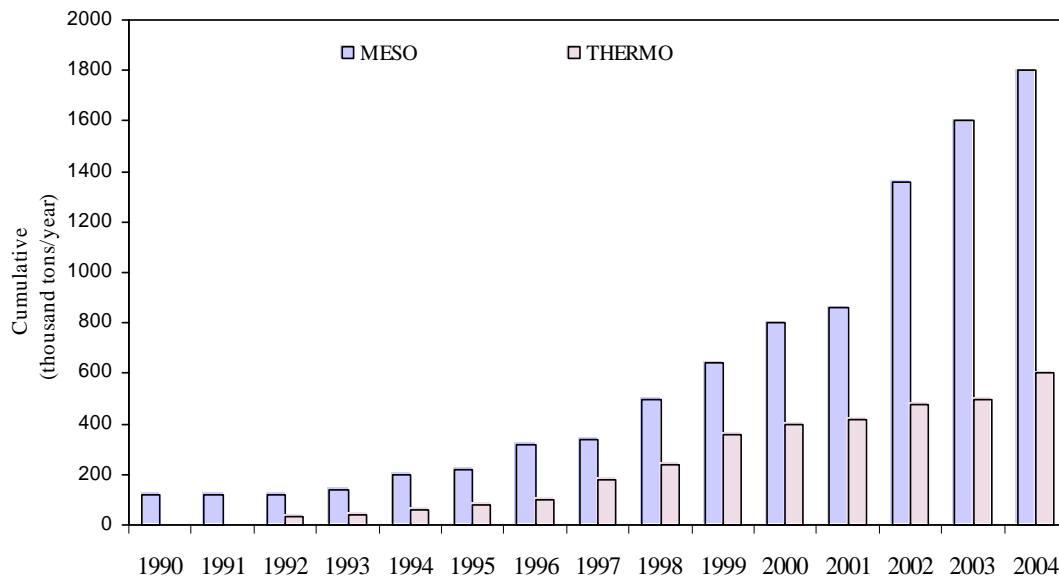


Figure 2.6 Shares of mesophilic and thermophilic digestion systems (Baere et al., 2003)

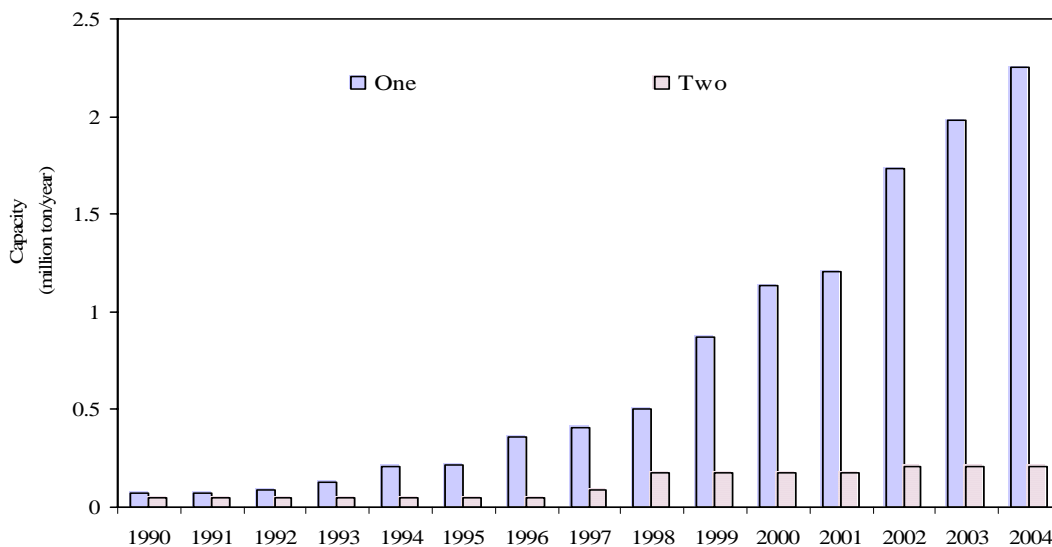


Figure 2.7 Market shares of single-step and multi-step plants (Baere et al. 2003)

2.11.2 Low Solids Versus High Solids

Based on solid content of substrate, digestion can be classified into:

- Low-solid anaerobic digestion digester where a large amount of water is added to get total solid of feedstock of less than 8%
- Semi solid (semi liquid) anaerobic digestion digester: have the solid content of 7-15%

- High-solid anaerobic digestion digester: the feedstock used as a dry solids content of 20-40%. No water or little water is added.

Nowadays, both types of anaerobic digestion processes are low solid and high solid used for the organic fraction of MSW clear technology trend can be observed at this moment. The biogas yield and production rate is high in systems where the waste is kept in their original solid state wherein it is not diluted with water. In deed, dry systems have already proven reliable in France and Germany for the biomethanization of mechanically sorted OF-MSW.

The specific features of high solid batch system such as simple design and process control, small water consumption and lower investment cost make them particularly attractive for developing countries. However, to some extent this system demonstrated various limitations that include heavy inoculation, mixing, and possibility of instability and also difficult to overcome instability (O'Keefe et al., 1993). In order to overcome this limitation, SEBAC process was developed and known as a proven technology that could overcome problems associated with inoculation, mixing and instability that frequently occur with other anaerobic reactor designs (Chynoweth et al., 2003).

2.11.3 Batch and Continuous Processes

In batch process, the reactor vessel is loaded with raw feedstock and inoculated with inoculums. It is then sealed and left until thorough degradation has occurred. The digester is then emptied and a new batch of organic mixture is added.

Table 2.9 Advantages and disadvantages of batch system

Criteria	Advantages	Disadvantages
Technical	Simple Low-tech Robust (no hindrance from bulky agent)	Clogging Need for bulking agent Risk explosion during emptying of reactor
Biological	Reliable process due to niches and use of several reactor	Poor in biogas yield due to channeling of percolate Small OLR
Economic and Environmental	Cheap, applicable to developing countries Small water consumption	Very large land acreage required (compared to aerobic composting)

In continuous process, the reactor vessel is fed continuously with digestate material. Fully degraded material is continuously removed from the bottom of the reactor.

The main difference between these two methods is that in the batch process, never a steady state situation is reached, whereas in the continuous process, this is a pre-condition. In the batch set-up, intermediates such as VFA and H₂ can accumulate with time, which change the process conditions (Mata-Alvarez et al., 2003). Table 2.9 shows the specific features of batch processes, such as a simple design and process control, robustness towards coarse contaminants, and lower investment cost make them attractive for developing countries (Ouedraogo, 1999).

2.11.4 Multi-phase versus single-phase digestion

In single-step process all digestion occurs in one reactor vessel. Multi-step process consists of several reactors and often the organic acid forming stage of the anaerobic digestion process (acetogenesis) is separated from the methane forming stage (methanogenesis). Table 2.10 and 2.11 present the advantages and disadvantages of one-stage dry system and two-stage system.

Table 2.10 Advantages and disadvantages of one-stage dry system

Criteria	Advantages	Disadvantages
Technical	No moving part inside reactor Robust No-short-circuiting	Wet wastes (< 20 % TS) can not be treated alone
Biological	Less VS loss in pre-treatment Larger OLR (high biomass) Limited dispersion of transient peak concentrations of inhibitors	Little possibility to dilute inhibitors with fresh water
Economic and Environmental	Cheaper pre-treatment and smaller reactor Complete hygienization – Very small water usage – Smaller heat requirement	More robust and expensive waste handling equipment

Source: Mata-Alvarez et al. (2003)

Table 2.11 Advantages and disadvantages of two-stage system

Criteria	Advantages	Disadvantages
Technical	Design flexibility	Complex
Biological	More reliable for cellulose –poor chicken waste Only reliable design for C/N < 20	Smaller biogas yield (when solid not methanogenized)
Economic and Environmental	Less heavy metal in compost	Larger investment

Source: Mata-Alvarez et al. (2003).

Bernal et al., (1992) observed that, under thermophilic conditions, if the feedstock is high biodegradability (as with market wastes), the rate of acidogenesis may create more acids than that can be converted by methanogenesis, affecting the stability of the process. This problem could be overcome by using separate reactors. Disadvantage of single stage systems however can be overcome by co-digesting these more problematic wastes with other materials and biological reliability can be improved by buffering and mixing. Hence, as Figure 2.7 shows multi-step processes shares of single-step and multi-step plant.

2.12 Co-digestion

An interesting option for improving yields of anaerobic digestion (AD) of solid wastes is co-digestion. That is, the use of a co-substrate, which in most cases improves the biogas methane production yields due to positive synergisms that establish the digestion medium and the supply of missing nutrients by the co-substrates. Sometimes the use of a co-substrate can also help to establish the required moisture contents of the digester feed.

Other advantages are the easier handling of mixed wastes, the use of common access facilities and the known effect of economy of scale.

Co-digestion with animal manure: The organic fraction of the MSW is mixed with animal manure and the two fractions are co-digested. This improves the carbon/nitrogen ratio, alkalinity and buffering capacity as well as gas production.

Digestion of OFMSW alone: The feedstock contains the organic fraction of MSW alone, slurried with liquid, and no other materials are added.

The co-digestion of municipal solid waste with animal manure/sewage slurry is a popular method in existing plants, as the process tends to be simpler and is economically more viable than only MSW (Hartmann and Ahring, 2004). However, some drawbacks also exist mainly due to slurry waste transportation costs and the problems arising from the harmonization of different policies of the waste generating facilities generators.

2.13 Post treatment

After anaerobic digestion is completed, the remaining biodegradable solid waste residues are commonly subjected to post treatment. Such treatment includes dewatering, aeration, and leachate treatment. The purpose of aeration as post treatment is to remove lingering organics, to aerobically reduce the compounds and to produce valuable products such as fertilizer and soil conditioner. The digested leaving the reactor is a thick sludge with the moisture content of about 80%. Transportation of digestate is uneconomic and digested residues are normally dewatered. The solid is reduced to a liquid content of about 50- 70%.

According to Mata-Alvarez and Sans (1995), the organic acids produced in the leachate could be recovered and processed further as illustrated in figure 2.8. These acids could be used to produce methyl or ethyl esters wherein considering their elevated octane numbers (between 103 and 118) could be advantageously used as an additive for gasoline.

2.13.1 Composting

There are certain advantages of post aerobic process of digester residue. One advantage is oxidation of reduced residue (ammonia, sulfides, organic acids), and the other is the reduction in pathogen killed off. (Rao et al., 2000). Technologies for composting can broadly be classified as agitated and static methods. In the agitated technique, the material to be composted is agitated periodically to allow oxygen, whereas in static method the composting material remains static and air is blown through the material. The windrow is widely used agitated method, and aerated static pile is one of the most common static methods available. On comparative study on windrow and static piles shows that windrow stabilizes rapidly than static piles (Gunasekera, et al., 2004).

A windrow is a pile with triangular cross section large enough to generate sufficient heat and yet, small enough to allow oxygen to diffuse to the center of the pile. The pile is placed on the firm surface and turned frequently to reintroduce air and to increase porosity. A high rate windrow composting system is turned up once to twice a week while maintaining the temperature at 55°C (USEPA, 1995). Turning of piles may release offensive odors, especially when the inner portion of the pile has low level of oxygen.

Aerated static pile method requires the composting mixture to be placed in piles that are mechanically aerated using networks of pipes fitted with blowers. Air is introduced to provide oxygen needed for biological conversion, and to control the temperature within the pile. The material is composted for three to four weeks, and cured for four or more

weeks. Bulking agent may be used to absorb water, if required. However, dry materials like MSW or yard waste or mixture may not need bulking agents.

The composting method accomplished in an enclosed vessel or container is known as in-vessel composting. Various types of vessels including vertical towers, horizontal rectangles, circular tanks, etc. have been used as reactors in this system. Two types of in-vessel composting methods are available namely; plug flow and dynamic (agitated type). A plug flow vessel operates on the principle of first-in, first-out where as a dynamic system requires composting material to be mixed mechanically. The in-vessel system is popular because of its odor control, faster throughput, lower labor cost and smaller area requirement.

2.14 Sequential batch anaerobic digestion

This system involves sequential staging in high solids leached bed reactors. As illustrated in figure 2.9, a coarsely shredded feedstock is placed into a bioreactor that is ready for a new cycle. Leachate from a nearly completed old bioreactor is recycled between that reactor and newly loaded reactor providing moisture, inoculum, nutrients and buffer necessary for start-up. Volatile organic acids formed during start-up are removed via leachate recycle to the active mature bioreactor for conversion to methane and carbon dioxide. After start-up a newly loaded bioreactor becomes a methanogenic mature reactor and is maintained by recycling leachate upon itself. Near the end of the process, approximately three weeks, leachate from the new mature reactor is used for the start up of a new reactor that is once again ready to begin a new cycle. It should be noted that biomass is not moved during the process; it progresses through these three stages during the course of a run. Start up of subsequent runs improved until the fourth run, in which kinetics was reproducible with the same feedstock.

Hydrogen:	$4\text{H}_2 + \text{CO}_2$	\longrightarrow	$\text{CH}_4 + 2\text{H}_2\text{O}$
Acetate:	CH_3COOH	\longrightarrow	$\text{CH}_4 + \text{CO}_2$
Formate:	4HCOOH	\longrightarrow	$\text{CH}_4 + 3\text{CO}_2 + 2\text{H}_2\text{O}$
Methanol:	$4\text{CH}_3\text{OH}$	\longrightarrow	$3\text{CH}_4 + \text{CO}_2 + 2\text{H}_2\text{O}$
Carbon monoxide:	$4\text{CO} + 2\text{H}_2\text{O}$	\longrightarrow	$\text{CH}_4 + 3\text{H}_2\text{CO}_3$
Trimethylamine:	$4(\text{CH}_3)_3\text{N} + 6\text{H}_2\text{O}$	\longrightarrow	$9\text{CH}_4 + 3\text{CO}_2 + 4\text{NH}_3$
Dimethylamine:	$2(\text{CH}_3)_2\text{NH} + 2\text{H}_2\text{O}$	\longrightarrow	$3\text{CH}_4 + \text{CO}_2 + 2\text{NH}_3$
Monomethylamine:	$4(\text{CH}_3)\text{NH}_2 + 2\text{H}_2\text{O}$	\longrightarrow	$3\text{CH}_4 + \text{CO}_2 + 4\text{NH}_3$
Methyl mercaptans:	$2(\text{CH}_3)_2\text{S} + 3\text{H}_2\text{O}$	\longrightarrow	$3\text{CH}_4 + \text{CO}_2 + \text{H}_2\text{S}$
Metals:	$4\text{Me}^\circ + 8\text{H}^+ + \text{CO}_2$	\longrightarrow	$4\text{Me}^\circ + \text{CH}_4 + 2\text{H}_2\text{O}$

Figure 2.8 Principal methanogenic reactions

According to O'Keefe et al. (1993) SEBAC worked with OFMSW, the results showed that the system had proved stable, reliable, and effective results of this study also showed that methane yield was 0.19 m³/kg VS after 42 days and mean of VS reduction was 49.7%. Chugh et al. (1998) showed that when we used proper leachate, we can increase rate decomposition of waste. This study also demonstrated that average yield was 0.18 m³/CH₄ kg volatile solids in two months. The process solves the disadvantages of a batch system by use inoculation in start-up stage. They found that microorganisms had been acclimatized well with environment in a fresh waste bed, when we use inoculums. Mohee & Ramjeawon, (2003) had been studied in SEBAC, they used periodic leachate recirculation in two reactors. They found that amount of VFA from 140 meq/l to 60 meq/L after 60 days.

2.14.1 Leachate Recirculation

One of the most critical parameters affecting solid waste biodegradation was found to be the moisture content, which could be controlled via leachate recirculation. (Vavlin et al., 2002). It was proved by the same author that a combination of leachate recirculation and pH adjustment could reduce the acidity of landfill and accelerate the rate of waste degradation. The organic content of leachate is dependent upon the kind of decomposition conditions (aerobic, anaerobic acidogenesis and methanogenesis). With acidogenesis, VFA has high COD and BOD₅. Low organic pollution is there in leachate for methanogenesis. The concentration of source inorganic compounds such as Fe, and Ca are caused by change in pH. Ammonia shows a slow increase with landfill age.

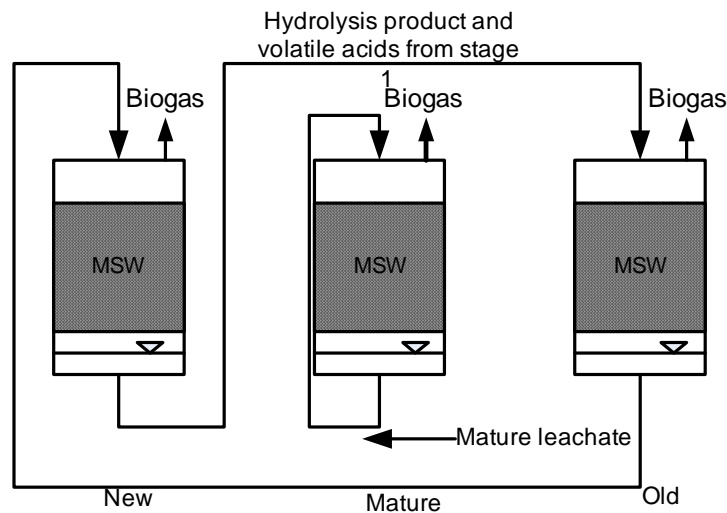


Figure 2.9 Configuration of leachate recycles patterns in different batch system (Chynoweth et al., 1992)

Leachate recirculation is one of the ways to provide and control moisture content of the waste. In the landfill, where most bio-reactions take place to stabilize solid waste, the lack of water sometime is responsible for retarding the degradation of MSW. In addition, the moisture that may be present is seldom uniformly distributed. Control and management of the liquid flow in the anaerobic digestion process will be enhancing degradation. According to Chugh et al. (1998), the flow of moisture is essential to mobilize nutrients and evenly distribute microorganisms through the waste bed. In addition, the movement of

moisture through a waste bed also provides mass transfer, and prevents the development of stagnant zones. These further confirm the role of leachate recirculation.

The moisture content may not only aid in bacteria movement but is also known to influence the mass transport limitation on a high solid bed and the balance between volatile fatty acids production by acidogenic bacteria and the conversion of acids to methane by methanogens (Ghost, 1985)

Chapter 3

Methodology

3.1 Introduction

Organic fraction of municipal solid waste (MSW) can be digested by varieties methods. Anaerobic digestion is one of the attractive method because the method has opportunity to recover methane as well as the digestate can be utilized as fertilizer. In the sequential batch process, the leachate of fresh reactor is circulated with another mature reactor. The mature reactor provides nutrients and bacteria from to the fresh filled reactor and removing volatile organic acids. Fermentation products such as volatile acids formed during start-up are removed inside the mature reactor where they are converted to methane.

This study was conducted in to two phases. In the first phase, Biochemical Methane Potential (BMP) tests was be conducted in lab-scale experiment. In the second phase, sequential batch anaerobic digestion of organic fraction of municipal solid wastes was carried out in pilot-scale set-up. Solid wastes was collected from AIT campus. The details of these two phases were discussed on the following sections.

3.2 Biochemical Methane Potential (BMP) test

A. Materials and equipment needed to conduct BMP test

- Shredding to reduce waste particle size into fine solids as possible
- 2.5-liter glass bottles with thick rubber septum were used as reactors. The exact volume of each bottle was determined by filling the bottles with measured volume of water
- An incubator of 37°C was used for the incubation
- Fresh inoculum was taken from anaerobic (mesophilic) wastewater treatment plant
- A 1 ml glass syringe with pressure lock allowed sampling of a fixed volume at actual pressure from the reactors
- Gas composition was done by gas chromatograph
- Gas mixture of 80% N₂ and 20% CO₂ (alternatively 100% N₂ gas can be used)

B. BMP test procedure

The BMP assay is usually carried out to determine the potential methane generation. The method is rapid and inexpensive in order to determine methane yield, methane production rate and organic matter reduction. The result of this method were used as indicator for evaluate the performance of anaerobic digestion process. Detail procedure was as described by Hansen et al. (2004). The figure 3.1 illustrated the procedure of this test.

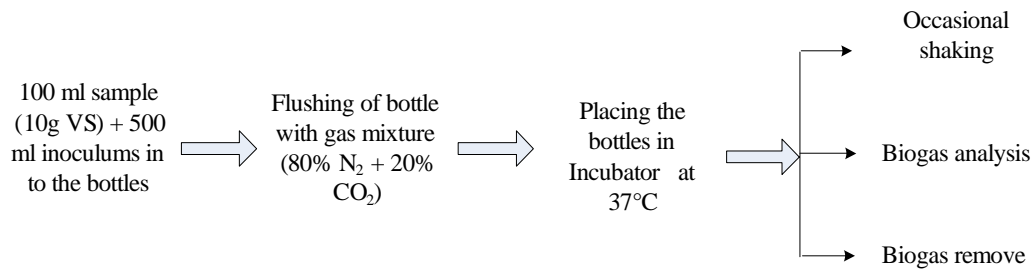


Figure 3.1 Schematic representation of lab-scale (BMP test) procedure

3.3 Sequential batch anaerobic digestion (pilot scale)

3.3.1 Feedstock preparation

The organic fraction of AIT wastes is high in biodegradable organic material that consist mainly of redundant foods, vegetable traps, spoiled fruit peelings with relatively high moisture content and volatile solid. In this study, the waste had moisture content around 75-80% and volatile was 80-90%.

Bio-waste of anaerobic digestion was prepared in following methods:

- Solid waste was taken form cafeteria and household in AIT campus
- Waste was shredded for the particle size reduction to approximately 30mm
- Finally, in order to avoid local blocking especially leachate circulation and create the space for gas and leachate flow to pass though. The bulking material like bamboo cutlets was added in system (totally 10% of working volume)

3. 3.2 Reactor design and configuration

The experiment was conducted in four plastic reactors. Each reactor had a total volume 238 liter; the working volume of each reactor was 158 liter. The reactor height was 90 cm and inside diameter was 58 cm and thickness of reactor wall 5mm.

The reactor was equipped with removable cover. Each batch solid was loaded and unloaded form the top by opening this cover. When closed reactor, a rubber buffer ring was put in between the cover and the reactor. Therefore, it could be fit well each other and without air leakages.

Solid separated by the perforated plastic net with size of mesh was 2mm, The depth of the gravel at the bottom of reactor was 15 cm for draining of leachate. The upper 15 cm of reactor was designed to provide allowable space for installation of revolving sprinkler that helps distributing uniformly the circulated leachate in to the system and provide a space for biogas generation. The figure 3.3 demonstrated detail configuration of a reactor and figure 3.5 illustrates sequential anaerobic digestion system.

3.3.3 Instruments/equipment need in SEBAC system

The main equipment needed in the pilot-scale experimental set-up consist of leachate tanks with the volume 200 L. Centrifugal were equipped pumping the leachate from leachate tanks through line and sprinkler to reactor. The air compressor pumped the air in to the waste bed before un loading in order to remove biogas to safer unloading. The drum type gas meters and wet gas meter was used to measure the daily volume of gas generated. the flow meters was used to control leachate circulation flow rate.

3.3.4 Pilot-scale experimental runs

Totally, the pilot experiment was divided in two runs. the concept layout of this experiment was showed in figure 3.2 and the specific objective for two runs were illustrated in figure 3.6.

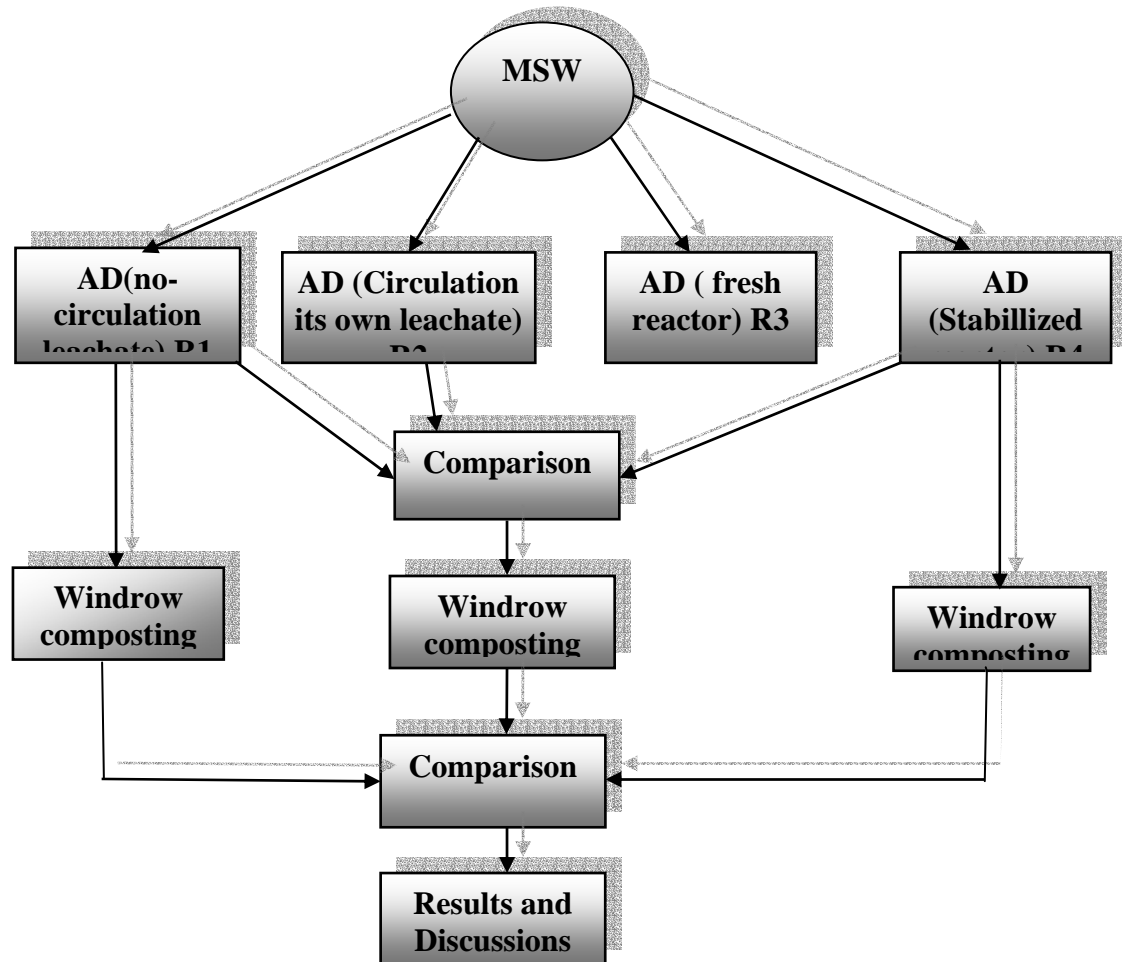


Figure 3.2 Conceptual layout of this experiment

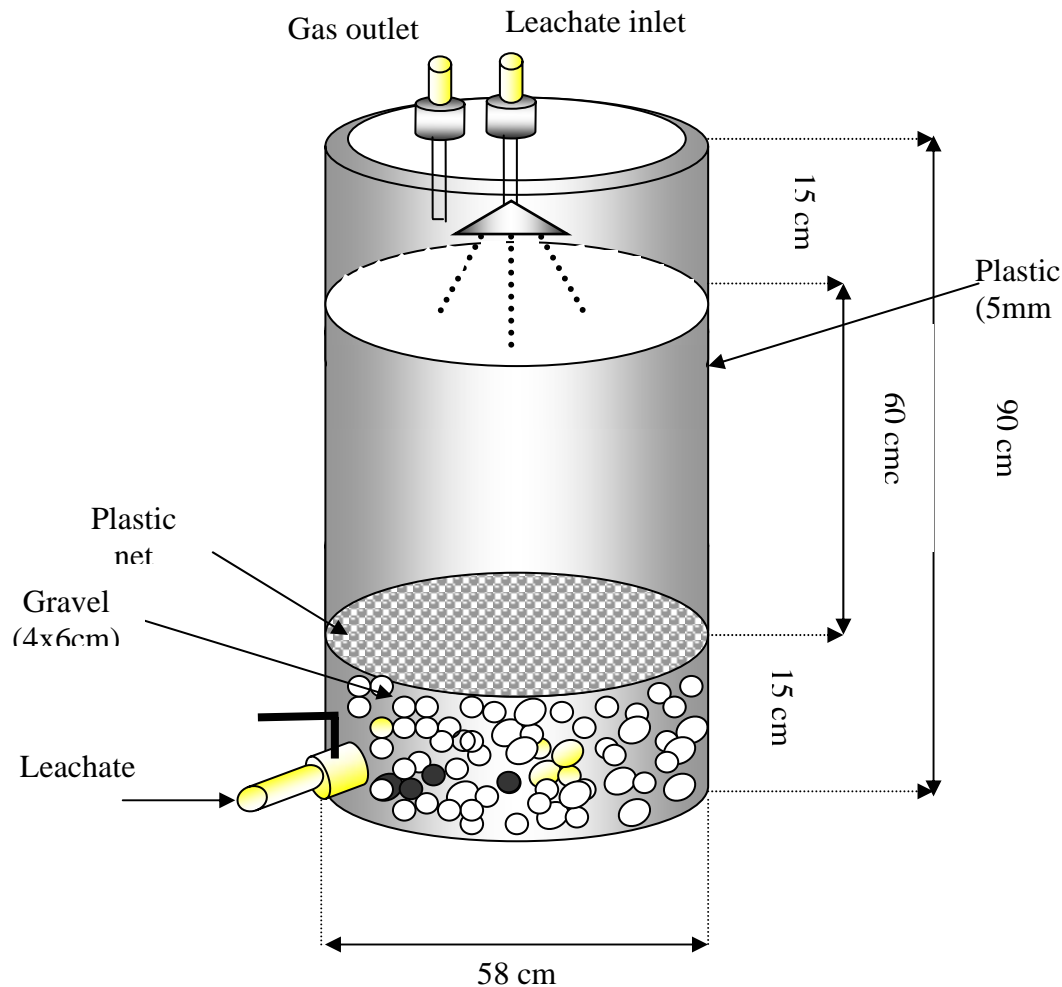


Figure 3.3 Anaerobic reactor design

3. 3.5 Sequential operation

The AD process involved two runs of digestion that occurred sequentially as conversion proceeds. In run 1, after shredding the wastes the size of waste was 30 mm and fed into the reactor 1 and reactor 2, reactor 3 was fed only the inoculums. R1 and R2 was filled with 50 kg solid waste in each reactor and inoculums addition was 50 %, ratio of carbon and nitrogen in solid waste was around 20. Anaerobic sludge and mixed cow dung were used as inoculums in reactor 1, 2 and 3. The reactor 2 was operated circulation of its own leachate. However, the reactor 1 was investigated is control reactor without leachate circulation. The reactor 3 was operated circulation of its own leachate, its objective created one reactors digested.



Figure 3.4 Photograph of the reactors

In run 2, when R3 was stabilized, it was used as old reactor. New reactor 4 was filled with fresh wastes & it was coupled with R3 for start up. Leachate was recirculated with cross circulation rate of 4L/min between reactor 3 and reactor 4. When pH and biogas composition of new reactor reached 7 and 50% respectively, the reactor (R4) assumed to be matured. Then old and new reactor were uncoupled. The new reactor (R4) was now operating on its direct circulation of its own leachate and was independent with old reactor. When biogas production in R3 is finished, it was aerated for 1-3 hours for safe unloading. Digested waste was post-treated in windrow composting. The figure 3.7 illustrates the process in sequential operation.

Digested waste from run 1 was subjected to post-treatment in a windrow composting. Specific of this process was described in item 3.6.

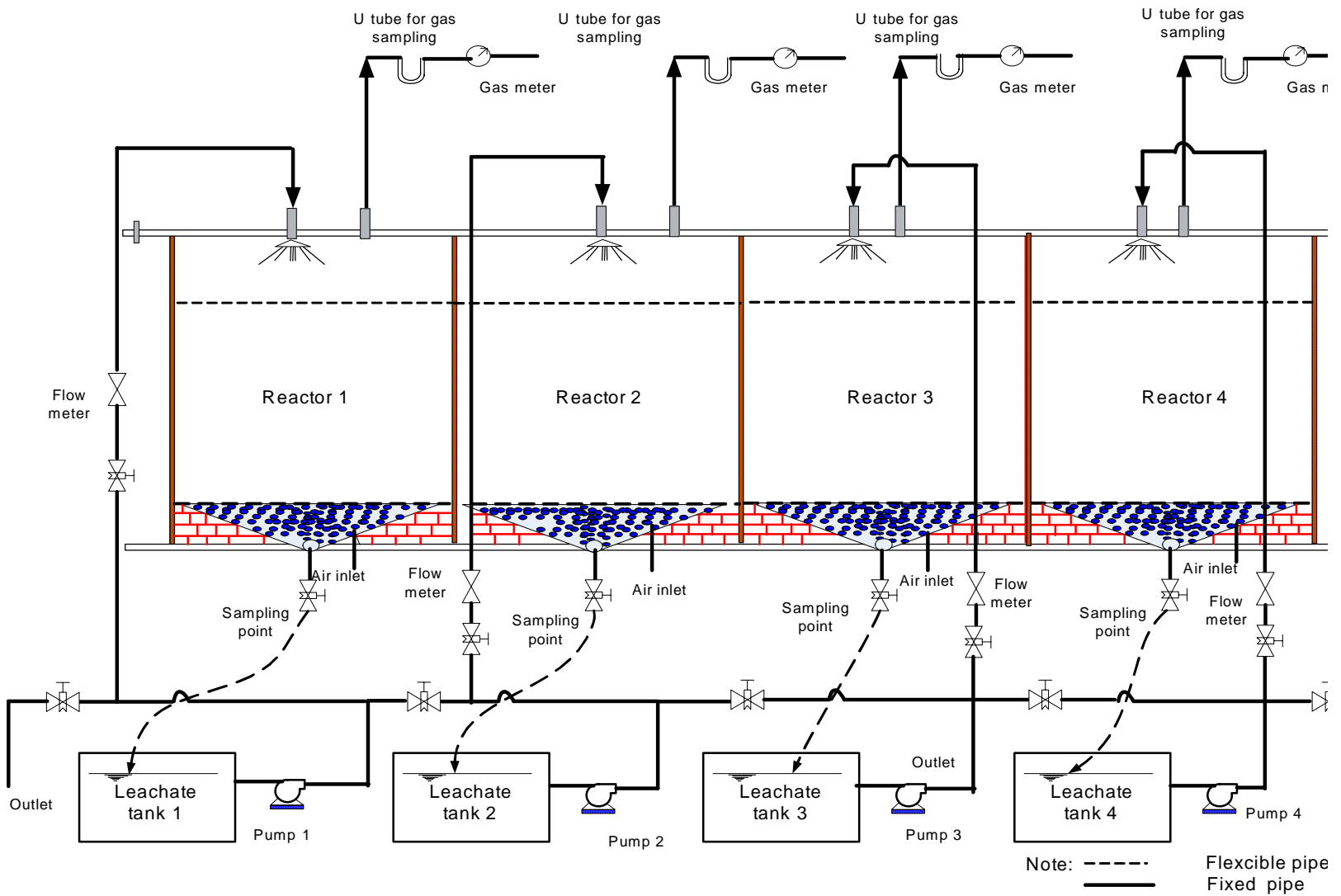


Figure 3.5 Sequential anaerobic digestion systems

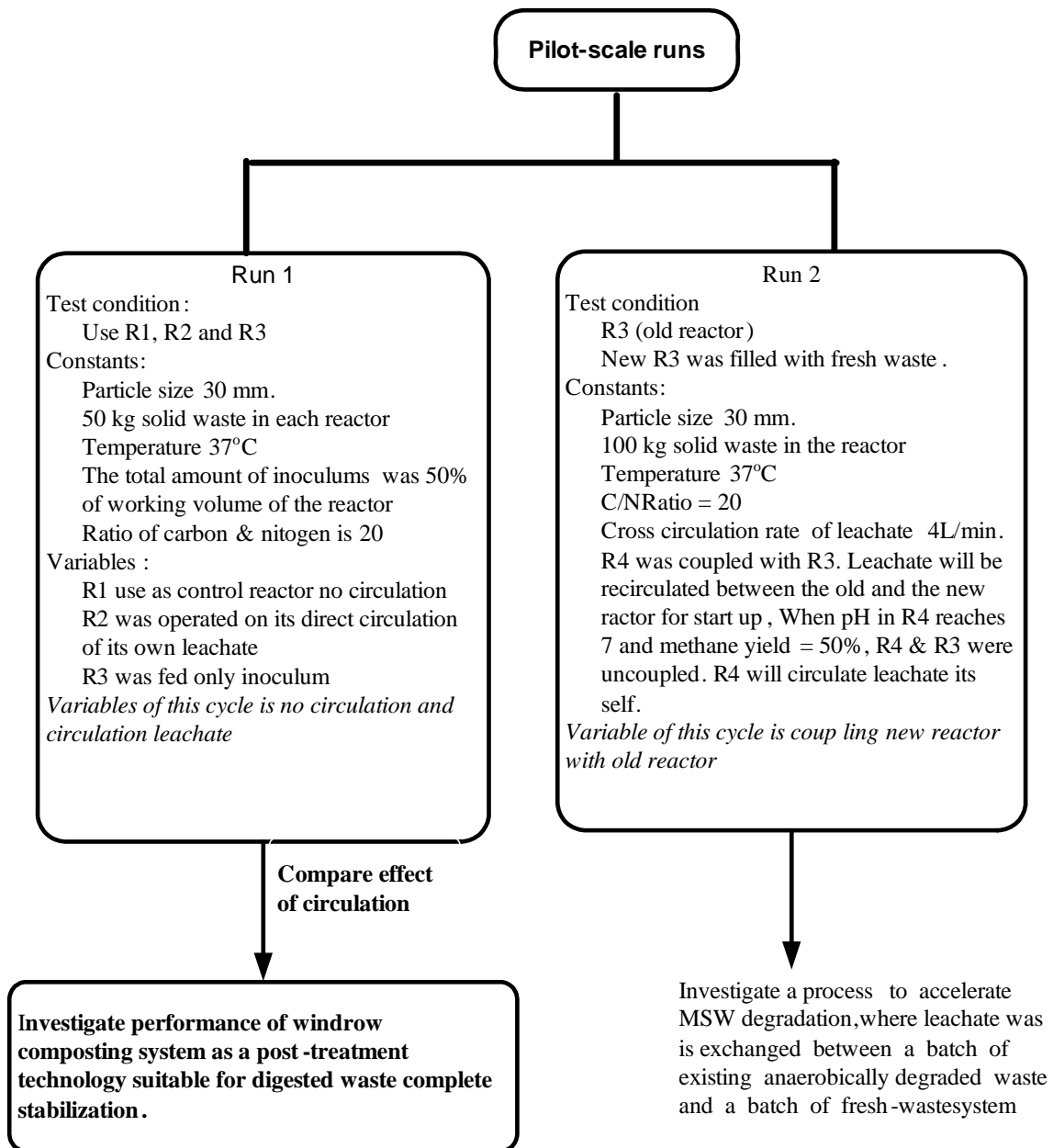


Figure 3.6 Schematic representations of the objectives of each experimental runs

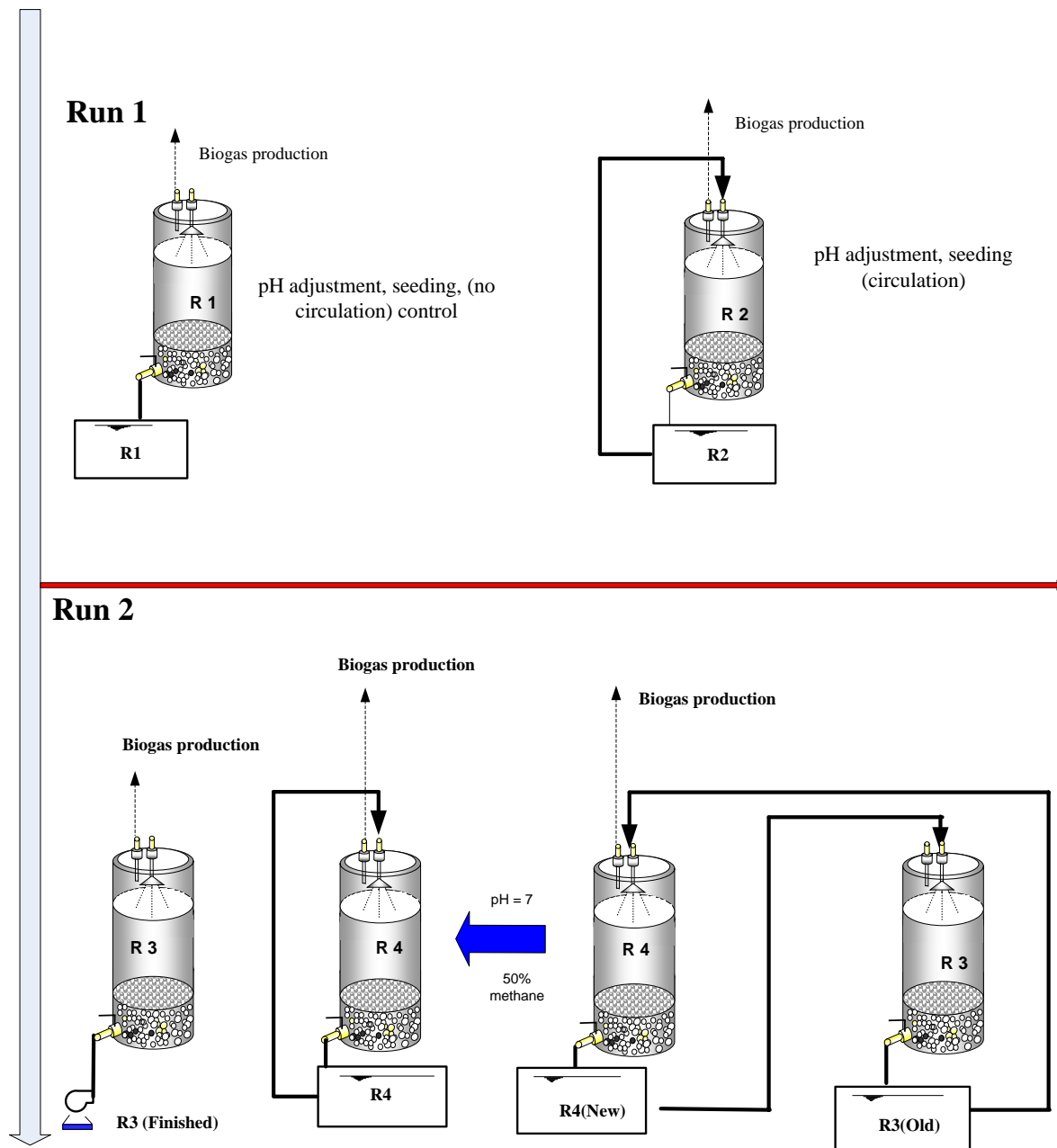


Figure 3.7 The process in sequential operation

3. 4 Windrow composting

For this study the digested waste, this was unloading from run 1. The initial moisture content, temperature, pH, volatile solid content and most of all the nitrogen content of the waste were all analyzed according to the methods mentioned in table 3.4. The configuration of composting piles were illustrated in figure 3.8

a, Temperature:

The temperature in each of the pile is recorded daily through out the composting period of three weeks. A compost thermometer was inserted in the pile and the temperature was

recorded when it reaches to equilibrium. Turning of the windrow pile was done without any fixed time frame. The turning of the pile in some case was done particularly when the pile temperature drops below 40°C during its first week and in some case when the incoming waste have moisture content higher than 75 % (wet basis).

b, pH:

Sample from the compost pile was taken from three different levels to obtain a representative sample.

- Spread compost in a thin layer in a pan, and dry for 24 hours in a 105-110°C oven.
- Weigh or measure 5 g samples of oven-dried compost into small containers.
- Add 25 ml distilled water to each sample.
- Mix thoroughly for 5 seconds then let stand for 10 minutes.

Read the pH with a calibrated meter or with pH paper and record as compost pH in water, or pH of waste.

Other portion of the sample was dried in the oven for 24 hours at 60⁰ C till a constant weight was obtained. The sample was then grounded to obtain particle size of less than 2 mm and following parameters was determined as given in table 3.4

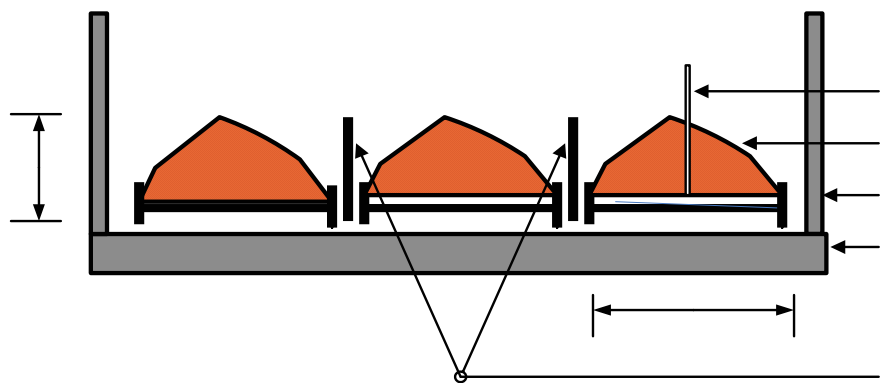


Figure 3. 8 Composting unit at the site

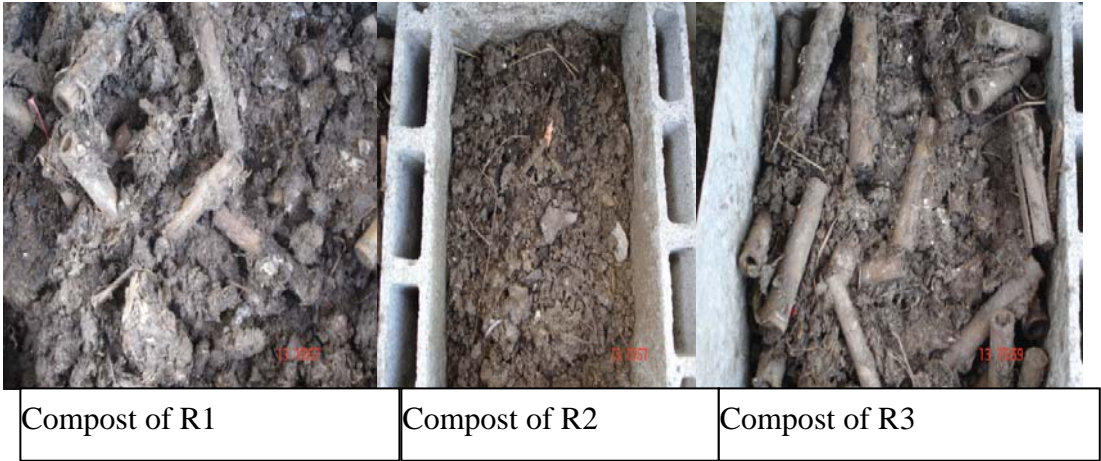


Figure 3. 9 Picture of Composting pile

3.5 Solid waste analysis

a, Moisture content determination

The moisture content and total solid will be determined by using Eq. 3.1 and 3.2.

$$\%MC = \frac{1000 - w_o}{1000} \times 100\% \quad \text{Eq. 3.1}$$

$$\%TS = 100\% - \%MC \quad \text{Eq. 3.2}$$

Where:

w_o = sample weight after drying at 105oC

b. Volatile solids determination

The volatile solid will be calculated by Eq. 3.3.

$$\%VS = \frac{w_o - w_f}{w_o - w_e} \times 100\% \quad \text{Eq. 3.3}$$

where:

w_o = weight of sample and crucible after 105°C

w_f = weight of sample and crucible after 550°C

w_e = weight of empty crucible

The sample after being dried will be grinded into a powder using a shredder. Then, it will be mixed well. Several grabbed samples each of size 2 g is put in evaporating dishes, which will be ignited at 550°C for one hour in a muffle furnace. The empty dishes will be weighed immediately before ignited. Initially, the solid samples will be evaporated to dryness in an oven at 103-105°C for at least 24 hour. Then the samples will be cooled in desiccators and weighed on an analytical balance. The cycle of drying, cooling, desiccating and weighing will be repeated until a constant weight obtained. The volatile solid of each dish will be calculated using Eq. 3.7. Final results will be the average value of all analyzed samples.

b. Calculation of % total solids (TS) and % total volatile solid (TVS) loss

Feedstock fed into reactor has two constituent, that are total wet weight of TW_o and dry weight M_o. when feedstock is digested, the residual of waste includes total wet weight TW₁ and dry weight M₁. The following Eq. 3.4 and 3.5 were used to calculate percentage total solid loss (%TS loss) and percentage volatile solid loss (%VS loss).

$$\%TS_{loss} = \frac{M_0 - M_1}{M_0} \times 100\% \quad \text{Eq. 3.4}$$

Where,

M_0 = dry weight of feedstock going in reactor, g

$$M_0 = TW_0 \times TS_0 \quad \text{Eq. 3.5}$$

TW_0 : wet weight of solid waste going in reactor, g

TS_0 : % total solid of feedstock (%TW)

$$M_1 = TW_1 \times TS \quad \text{Eq. 3.6}$$

Where:

M_1 : dry weight residual going out reactor, g

TW_1 : wet weight of residual going out reactor, g

TS_1 : % total solid of residual (%TW)

$$\%VS_{loss} = \frac{N_0 - N_1}{N_0} \times 100\% \quad \text{Eq. 3.7}$$

Where:

N_0 = Weight of volatile fraction of feedstock going in reactor, g

$$N_0 = M_0 \times VS_0 \quad \text{Eq. 3.8}$$

Where:

VS_0 : % volatile solid of feedstock (%TS)

$$N_1 = M_1 \times VS_1 \quad \text{Eq. 3.9}$$

Where:

N_1 : weight of volatile fraction of residual going in reactor, g

VS_0 : % volatile solid of residual (%TS)

3.6 Leachate characteristic analysis

The parameters of leachate was analyzed as following:

- pH
- VFA
- Alkalinity
- NH_4 -N, TKN

- Dissolved organic carbon (DOC)

3.7 Biogas analysis

- Gas production will be monitored daily on-line with a wet gas meter
- Biogas will be sampled by inserting gas syringe into U tubes, volumetric composition of biogas (H_2 , CO_2 , CH_4 , O_2 , N_2) sample will be analyzed daily by using Gas Chromatograph (SHIMADU-GC14A, Japan) equipped with Thermal Conductivity Detector (TCD).

3.8 Post-treatment of digested wastes

The digested wastes was further treated by aerobic composting to make it suitable for fertilizer. The windrow composting technique was used. In aerobic post-treatment, maturation and drying of the remaining solids takes place in enclosed windrows where compost is stored for a minimum of 2 weeks. Table 3.4 presents sample analysis methods for determination of total organic carbon, nitrogen, phosphorus and potassium along with precaution during sample analysis and handling. Calorific value will also be analyzed using bomb calorimeter.

Table 3.1 Solid waste analysis

Test Parameter	Method/ Instrumentation	Minimum sampling size
Moisture content (%)	Oven (105°C) for 24hrs Gravimetric analysis	1 kg
Total solids (%)	Gravimetric analysis	1kg
Total volatile solids (%)	Muffle furnace (550°C)	2 g

Table 3.2 Leachate characteristics analysis

Test Parameter (unit)	Method/ Instrumentation
pH	pH meter (pH 330 i, Germany)
COD (mg/L)	Standard method 5220C: Closed reflux titration method (APHA, 1998)
TOC /DOC (mg/L)	High temperature combustion method (SHIMADZU TOC-V _{CSN} Non-dispersive infrared analyzer detector with standard TC catalyst)
Alkalinity (mg/L as Ca CO ₃)	Standard method 2320 B: Titration method
VFA (mg/L)	Gas Chromatograph (GC-HP 5890 series II plus GC-6)
TKN (mg/L)	Standard method 4500B (APHA, 1998)
NH ₄ -N	Standard method 4500B (APHA, 1998)

Table 3.3 Biogas analysis

Test parameter (unit)	Method/Instrumentation
-----------------------	------------------------

Flow rate (L/day)	On-line Gas meter
Composition of different gas (%)	Gas Chromatograph (GC-14B GC-3)

Table 3.4 Digested Analyses

Test Parameter	Method/Instrumentation	Precaution during sampling and analysis
Nitrogen (%)	Total Kjeldahl method	
Carbon (%)	Estimated using total volatile solids %/1.8 (New Zealand Eng, 1951 and and Gotaas, 1956)	
Phosphorus (%)	Acid digestion /spectrophotometer	Not to boil to dry
Moisture content		
Potassium	Acid digestion & Inductively coupled plasma method: 3120B	Not to let it dry during digestion
Total solids (%)	Gravimetric analysis	
Total volatile solids (%)	Muffle furnace (550°C)	
pH	Compost extractions	
Temperature	Compost Thermometer	

Chapter 4

Results and Discussions

This chapter presents findings from pilot scale sequential batch anaerobic digestion (SEBAC) experiments and windrow composting of digested solid. The experiments on SEBAC were performed under ambient temperature conditions. In the later part of this chapter, results from laboratory scale, Biochemical Methane Potential (BMP), are also described to evaluate the process efficiency.

4.1 Sequential Batch Anaerobic Digestion (SEBAC)

After shredding the wastes to the size of 30 mm, it was fed into the reactor 1, 2 and 4. The ratio of carbon and nitrogen in solid waste was around 20. Each reactor was filled with 50 % solid waste and 50 % inoculums. Anaerobic sludge, digested and mix cow dung were used as inoculums. Bamboo cutlets (10 % of working volume) were used as bulking agent to facilitate the flow of leachate and gas. The reactor 2 was operated by circulating its own leachate whereas the reactor 1 is investigated as control reactor without leachate circulation. The reactor 4 (R4) used sequential leach-bed anaerobic digestion process under dry and ambient conditions.

A. Characteristics of feed and digested residue:

The dry matter content of solid waste was collected from AIT campus as 78% and 80% of the dry matter was volatile solid. Table 4.1 presented characteristic average values of feedstock. Analysis of feedstock samples was carried out in duplicate. 50 kg (14kg total volatile solid) and 97 kg solid waste wet weight (20 kg total volatile solid) were loaded into the R1, R2 and R4, respective. The packing density was 650 kg /m³ due to the addition of bamboo cutlets as bulking agent.

Table 4.1 Solid waste characterization

Experimental run	Density (Kg/m ³)	Moisture content (%w)	Total solid waste (%w)	Total Volatile solid (%w)
Run 1				
Reactor 1	650	78.71	21.28	84.68
Reactor 2	650	78.19	21.8	85.04
Reactor 3	(Inoculums reactor)			
Run 2				
Reactor 4	650	79.47	20.53	82.76

Comparing this result with previous studies in market waste, organic fraction of municipal solid waste (OFMSW) has higher total volatile solid content compared to only 5-10 % in Taklong municipality dumpsite.

B. Biogas production

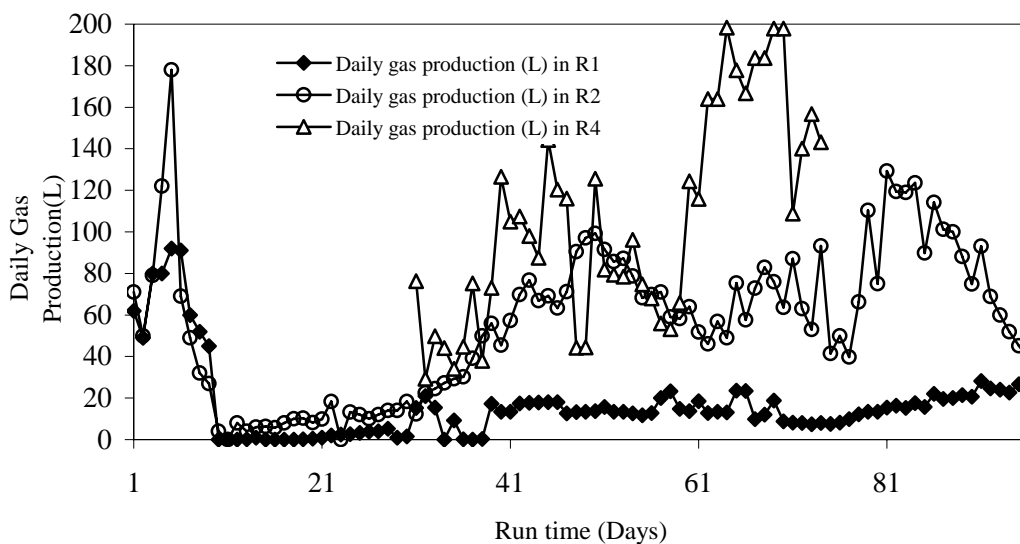


Figure 4.1 Daily biogas production in R1, R2 and R4

Figure 4.1 illustrates daily biogas productions of both reactors (R1 and R2) and R4. R1 and R2 were quite similar in the beginning. Afterwards, daily biogas productions of reactor R2 increased quickly, reached up to the peak of 129 L/day on day 81 (Table A-2a), and

then declined gradually due to limited organic compounds, after day 81 it steady increased as indicated by the steep decrease of COD values. In comparison, daily biogas productions of reactor R2 of reactor R1 exhibited a relatively steady pattern and ranged within 15-29 L/ day from day 42 to 96 (Table A-1a). At 96 days operation of experiment, the total biogas and methane yields were 5428 L in reactor R2, while only 1628 L in reactor R1. The higher amount of biogas yield in reactor R2 was well corresponding to the lower COD concentration at 96 days operation of experiment.

In leachate re-circulated reactor (R2) maximum gas production was observed on day 81 and its value was 129L/day (Table A-2a) after the commencement of the anaerobic digestion. In reactor without leachate recirculation (R1), the gas production rate was slow, the peak production rate of 29L/day (Table A-1a) was observed on 96 day. Therefore, leachate recirculation had further enhanced the degradation process as indicated by the improved rates in gas production and nutrient removal from R2. Pohland and Harper (1987) reported that it took a longer time to go through the initial adjustment, transition and acid formation stages before entering the methane production stages if the anaerobic degradation processes were not maximized in a landfill site. Kinman (1987) also demonstrated that unless better degradation conditions were provided, it took a long period of over a year to achieve maximum gas production in experimental cells.

In R4 , The exchange of leachate between the fresh-waste and stabilised-waste removed VFA from the fresh-waste through flushing toxicity. The continued indirect recirculation between the stabilised-waste reactor and the fresh-waste reactor served both purposes, which were the volatile fatty acids (VFA) produced by the fresh-waste (which reduce the system pH) were flushed out into the leachate. The acids were then removed and the leachate and when passed through the stabilised-waste reactor, carried the inoculum to seed the fresh-waste to speed up the degradation.

At the commencement of indirect recirculation, daily biogas production from a fresh-waste reactor increased rapidly and then dropped. The methane production rates of the leachate recirculation reactor (R2) and leachate exchange (R4), were compared. The results showed that different methane production rates from both reactors from day 10 to 45. The average methane production rate of R2 was 3 L/kg VS/d (Table A-2a) while that of R4 was 5 L/kg VS/d (Table A-3a). However, it was observed that R4 was in an acid phase while R2 was in a methanogenesis phase, as indicated by the increasing methane content and leachate pH and. This meant that circulation leachate with high inoculums and adjustment pH in the early acid phase helped stabilized reactor but did not result in higher methane yield rates.

C. Cumulative biogas production

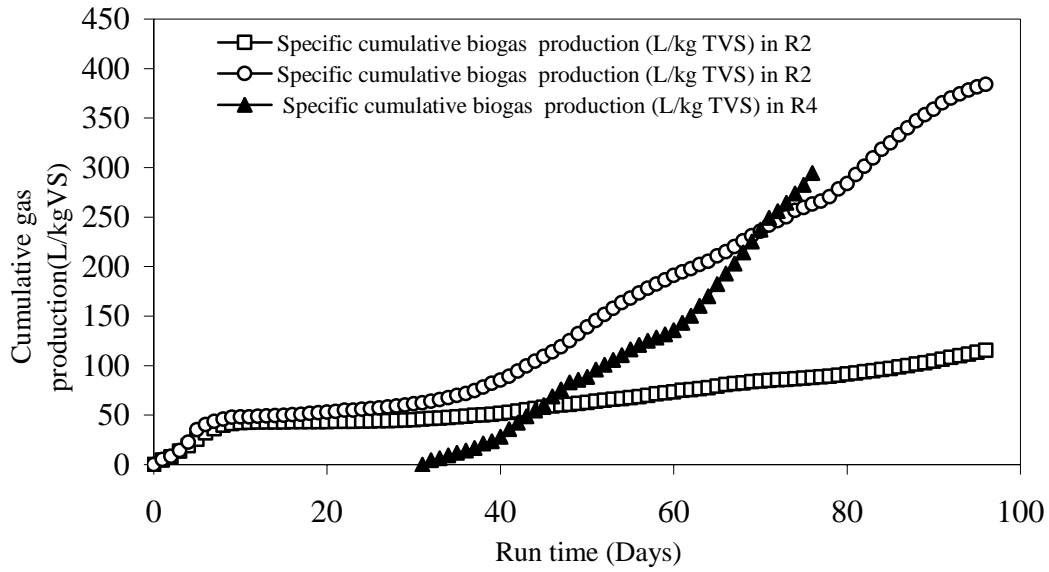


Figure 4.2 Cumulative biogas production in R1 and R2

Biogas cumulative production in R1 after 96 days of digestion was 115 L/kg VS (Table A-1a) while in reactor 2 (circulation reactor) higher generation rate was observed 384 L/Kg VS (Table A-2a). Biogas production in R4 after 46 days was observed 249 L/kg VS (Table A-3a) as shown in figure 4.2.

D. Biogas Composition

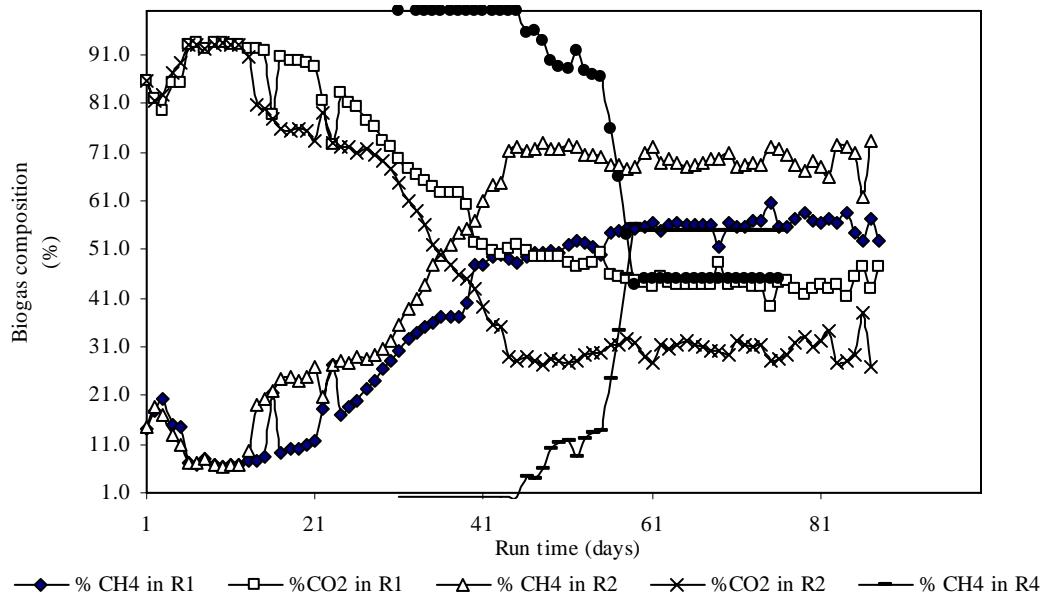


Figure 4.3 Biogas composition in R1, R2 and R4

Figure 4.3 shows that this biogas consisted mainly of carbon dioxide, which is the major product of fermentation reactions. Christensen and Kjeldsen (1989) reported

that as the anaerobic stage develops, the activity of the fermentative and acetogenic microorganisms is high, producing high concentrations of carbon dioxide and hydrogen in the biogas, with high concentrations of volatile fatty acids in the leachate. The concentration of carbon dioxide reaches its peak value during the acid formation phase and can reach as high as 85%. In the current study similar results were obtained, where carbon dioxide production was high during the peak production of volatile fatty acids, reaching values in the range of 75-90%. Hydrogen was also produced during the initial stages of anaerobic digestion.

As shown in figure 4.3, reactor R2 had an earlier initiation of methane production than reactor R1. On day 43, CH₄ content in biogas of reactor R2 increased to 64% (Table A-2a) while only 50% in reactor R1 (Table A-2a). The higher CH₄ content in biogas of reactor R2 could be attributed to the redistribution and transfer of nutrients by leachate recirculation.

From these results it can be concluded that the leachate recycle appeared to be somewhat beneficial in maintaining high methane composition. The propagation of methane producing bacteria was promoted with the leachate recycle and this promotion was further enhanced by adjusting the leachate recirculation rate.

Although methanogenesis can be suppressed in acidic environment, as evidenced by the rather low daily biogas productions during the initial stages, this process was not completely suppressed, as proved by 25% CH₄ contents in the biogas of reactors R1, when pH declined to 5.5–5.9. Paulo (2003) reported that the methanogenesis at pH 5.5–5.9 could be attributed to hydrogen-consuming methanogens present in organic wastes

From the figure 4.3, it is clear that methane composition reached to 50% of methane produced after 41 days operation and 36 days in R1 and R2 respectively. Speece (1996) demonstrated that this stage considered the beginning of mature phase or to ammonium bicarbonate alkalinity, which maintained a pH close to neutral.

In R4, monitoring the biogas production and its composition in CO₂ and CH₄ also made it possible to distinguish the phases of waste degradation (Figure 4.3). Farquhar and Rovers, 1973 reported that methanogenesis was marked by a methane production of approximately 50–60% and by a production out of carbon dioxide of approximately 40–50%.

The values obtained, it was possible to estimate that the methanogenesis phase was reached after 28 days of degradation for R4 (Table B-1c), which confirmed the conclusions obtained, starting from the pH of leachate analyses. In contrast, CH₄ content in biogas of reactor R2 obtained 50% after day 36 (Table A-2a). However, pH value of leachate in R2 reached to 7 in day 21 (Table B-1a) while this value was observed on day 27 in R4.

This meant that circulation leachate with 50 % inoculums and adjustment pH in the early acid phase helped maintain neutral pH but did not result in higher methane composition.

E. pH

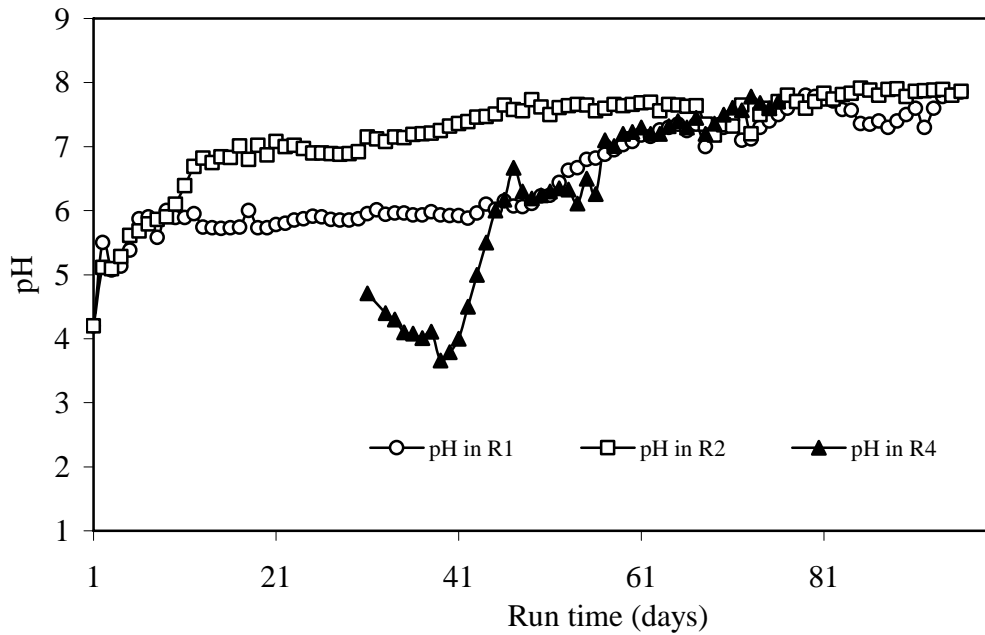


Figure 4.4 Variation of pH in R1, R2 and R4

The pH of the effluent leachate from R2 rose from its initial value of 4.21, prior to the commencement of direct recirculation, to 5.11 on day 2. Between day 3 and day 14, the pH slowly increased to 6.75. It then rose steadily to 6.8 from day 14 to 16. From day 17 to 80, the pH rose steadily to about 7.8 (Table B-1b). From day 17 to day 36, the pH remained stable at a value around neutral. There was no significant change in the pH value of 7.4 between day 36 and 96. In contrast, the pH values of reactor R1 increased slowly and kept no more than 6.9 until day 58 (Table B-1a), which was described in figure 4.4.

According to studies of Kruempelbeck (1999) and Inancet (1996), methanogenesis was favored at a pH 6.4–7.2 and suppressed to some extent in acidic environment. Therefore, the relatively lower pH level in reactor R1 during the experiment could be partially responsible for the retarded conversion of organic materials. Low pH values observed in R1 could be attributed to the production of low alkalinity, which was not enough for maintaining the neutral pH and buffering the VFA produced.

A higher pH in the fresh-waste accelerated acid production also, to such an extent that the pH value started to drop, due to accumulation of VFAs. Pohland and Kang (1974), and Robinson and Maris (1979) reported that although control of pH and initial seeding enhanced the decomposition of waste, these factors provided a favourable environment for the acid formers and were therefore unfavourable to the methane formers.

The pH of the R 4 decreased to 4.71 on day 1, but decreased to 4.4 by day 2 and from day 3 to 25 varied between 4.3 and 6.5 (Table B-1c). It then rose steady about 7 from day 26 to 46. The pH of the effluent leachate dropped initially but picked up, reaching neutral

on day 26. This indicated that there were other factors a part from VFA concentration involved in controlling pH in start-up reactors.

This may be attributed to the highly buffered leachate from the mature reactor. This indicated that there was a threshold limit for methane generation rate around pH 7. This is a similar finding to that determined by Vavilin et al. (2006), which showed that inhibition is related either directly or indirectly to low pH. The relationship between methane rate and pH is stronger than that observed between pH and VFA concentrations.

The results indicated that pH of R2 rose 7 on day 17 while R4 reached same value on day 26. But methane composition in R2 rose 50% on day 34 while in R4 was day 28. This meant that with seeding high inoculums could help increase buffer but it would not increase methane composition. Though the coupling of the reactors was sufficiently well inoculated and buffered to overcome this imbalance quite quickly. The uncoupling of the reactors also saw a rapid increase in biogas production. The methane content in the biogas from the fresh-waste reactor reached its final value of 58% on day 29.

The addition of a buffer compound (NaOH) provided the environment required for methanogens to utilize substrates and methane composition and production rapidly increased. The leachate recirculation reactor (R2) reached the pH neutral value more quickly than the leachate exchange reactor (R4) (day 17 for R2 and day 27 for R4). However, the leachate exchange reactor (R4) provided a greater biogas production rate (2 /kg VS/d from R2 and 4L/kg VS/d from R4).

It meant that leachate exchange reactor (R4) enhances methane production.

F. TKN and Ammonia

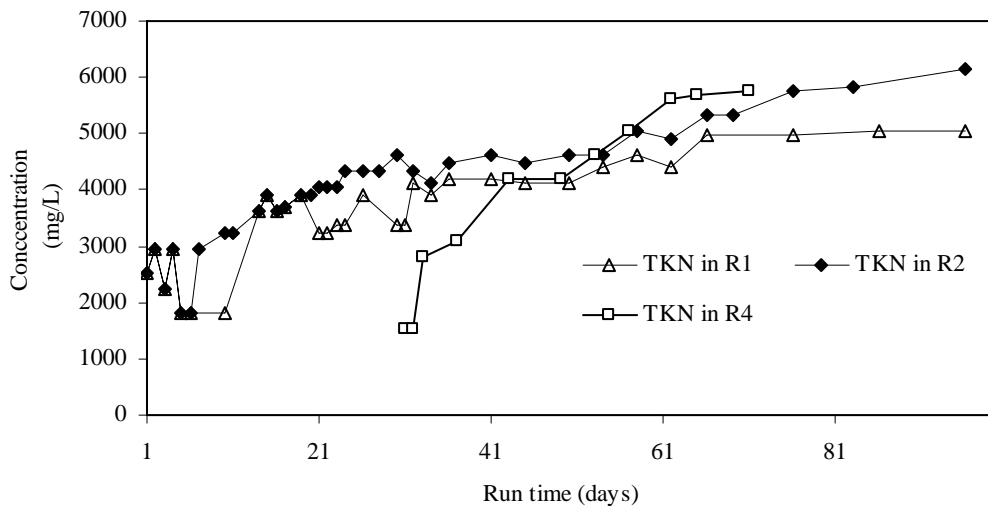


Figure 4.5 TKN concentrations in R1, R2 and R4

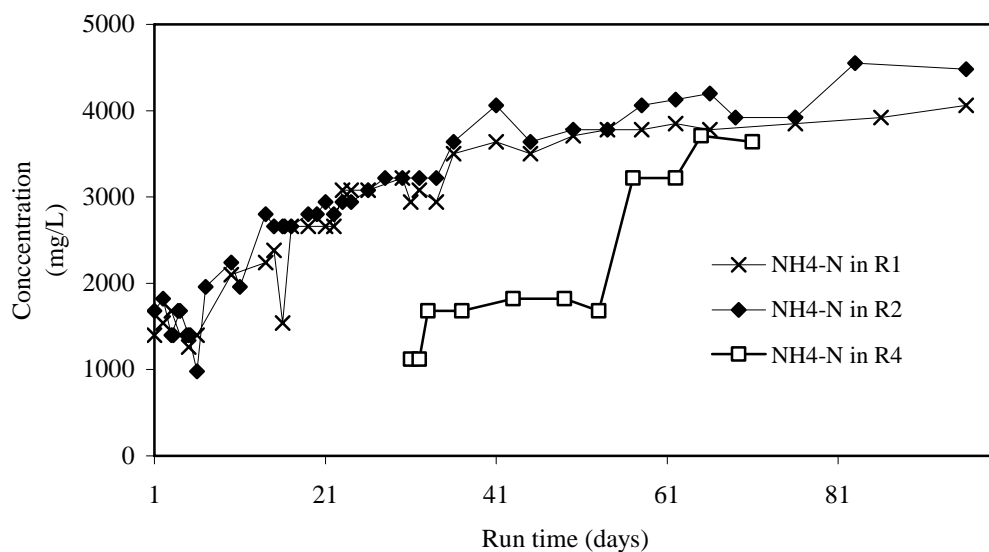


Figure 4.6 Ammonia concentrations in R1, R2 and R4

The initial concentrations of ammonia–nitrogen in both reactors were found to be different, indicating the heterogeneity in ammonia–nitrogen content in all reactors, although the anaerobic reactors were loaded with the same mixture of municipal solid wastes. Figure 4.5 showed the trends in ammonium concentration in leachate produced from the R1, R2 and R4.

The ammonia–nitrogen was found at high concentrations in the municipal solid waste as a result of decomposition of organic matter containing nitrogen such as protein and amino acids. As a result of degradation of these nitrogenous organics the ammonia–nitrogen concentrations increased from 1400 and 1680 mg/L to a maximum of 4060 and 4550 mg/L (Table B-1b), respectively, in the R1 reactors and R2 reactor. The highest ammonia concentrations were measured to be 3710 mg/L for R4 (Table B-1).

The recirculation practice in the recycled reactors reintroduced ammonia to the system keeping its value as high as 4550 mg/L through day 83. Therefore, ammonia–nitrogen concentration behavior was directly attributed to the leachate recirculation management strategy recirculated within the reactor providing an increased opportunity for accumulation and/or removal through biological nitrogen assimilation as reported by San and Onay (2001) and McCarty (1964).

Study of Jokela (2002) showed that on day 66 the ammonium concentration started to decrease, since the ammonia was consumed by the anaerobic bacteria to develop their cellular components. Chanet (2002) reported that ammonium concentration varied between 1000 and 1200 mg/l after 250 days of operation in landfill reactor operated without recycle.

Jokela (2002) reported that in landfills, the release of soluble nitrogen from MSW into landfill leachate continues over a long period compared to that of soluble carbon compounds. This was the main source of nitrogenic proteins, which accounts for approximately 0.5% of dry weight of MSW. Landfill leachate treatment is normally focused on the removal of organic matter and ammonia–nitrogen levels, which were quite

important for possible inhibition of methane production under anaerobic conditions and the leachate toxicity was significantly correlated with COD

Studies of Koster and Lettinga (1984) showed that that above a threshold total ammonia-N level of 1700 mg/L (under mesophilic conditions) could inhibit acetate-utilizing methanogens . However, The studies of Fujishima (2000) and Wiegant (1986) reported that acetate-utilizing methanogens were able to acclimate to total ammonia-N levels up to 4000 mg/L for mesophilic and thermophilic conditions.

Protein are hydrolyzed into acid amino acid and further converted into ammonia. Ammonia is end product in anaerobic digestion, Figure 4.5 illustrated daily concentration TKN in of total soluble nitrogen and ammonia nitrogen which could be reflex the daily hydrolysis of protein in anaerobic digestion. From this data, daily TKN concentration of leachate in R1 reached 5 g/L after 86 days (Table B-1a). However, daily TKN concentration in R2 reached same ammonia value after 58 days (Table B-1b) operation while daily TKN concentration of R4 leachate in reached same value on day 26 (Table B-1c).

Therefore, it can be concluded that leachate exchange with old reactor accelerated waste stabilization and enhances methane production.

G. COD

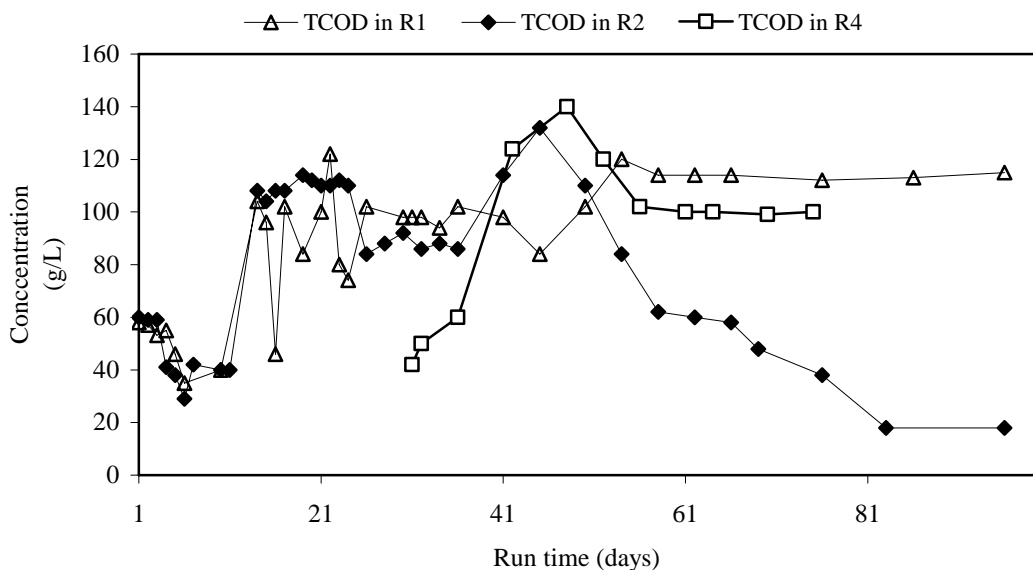


Figure 4.7 Trend COD concentration in R1, R2 and R4

After the onset of methane production, a reduction in leachate concentration is generally expected Barlaz (1987). However, Kinman (1987) and Warith (1999) reported that a 3 to 6 times increase in leachate strength via recirculation and a rapid increase in COD in pilot-scale waste cells within a short period . Chan (2002) indicated that recirculating leachate not only shortened the period to methanogenic stage but also lowered the leachate strength, in terms of COD, which depended on the portions of nutrients, minerals or organics being attenuated by the waste and soil in landfill cells. If effective attenuations are high, a lower strength of leachate was expected.

As showed in figure 4.7, the initial COD concentrations in reactors R1, R2 and R4 ranged within 57000–58,000 mg/L (Table B-1a), 59,000–60,000 mg/L (Table B-1b) and 42000–

50,000 (Table B-1c) , respectively. Although reactor R2 had a wider range of COD concentration than reactor R1 and R4, the average COD concentration contents were approximately equivalent, indicating the uniformity of the synthetic MSW placed in three reactors. Due to the rapid hydrolysis of organic MSW, COD concentration in three reactors increased fast and reached the first peak levels around day 19. For reactor R2, COD concentration in leachate collected from sampling port dropped dramatically to below 84 g/L on day 54. In contrast, COD concentrations in R1 reactor steady remain 100g/L. It meant that hydrolysis of organic MSW was considerably slow. Furthermore, on day 96 of experiment, the average COD value in R1 reactor was 115g g/L, while only 18 g/L R2 reactor. In brief, the degradation of MSW in R2 reactor was considerably faster than that in R1 reactor in terms of the COD concentration.

According to some studies, different suggestions were reported about the COD decrease in leachates. Chugh (1998) demonstrated that decreases in COD start within 15 days in a recirculated solid waste reactor. However, Bae (1998) showed that COD decreases start after about 100 days through anaerobic incubation. Similarly, Iglesias (2001) reported that the COD values decreased after about 215 days.

In R4, The results indicate that though the uncoupling of the reactors caused some initial distress to the fresh-waste, its pH trend shows that the waste bed was sufficiently well inoculated and buffered to overcome this imbalance quite quickly.

The trends of total COD showed that there were not clearly evident that anaerobic used exchange leachate faster than directly circulation leachate was faster in terms of COD concentration.

H. Specific cumulative methane production:

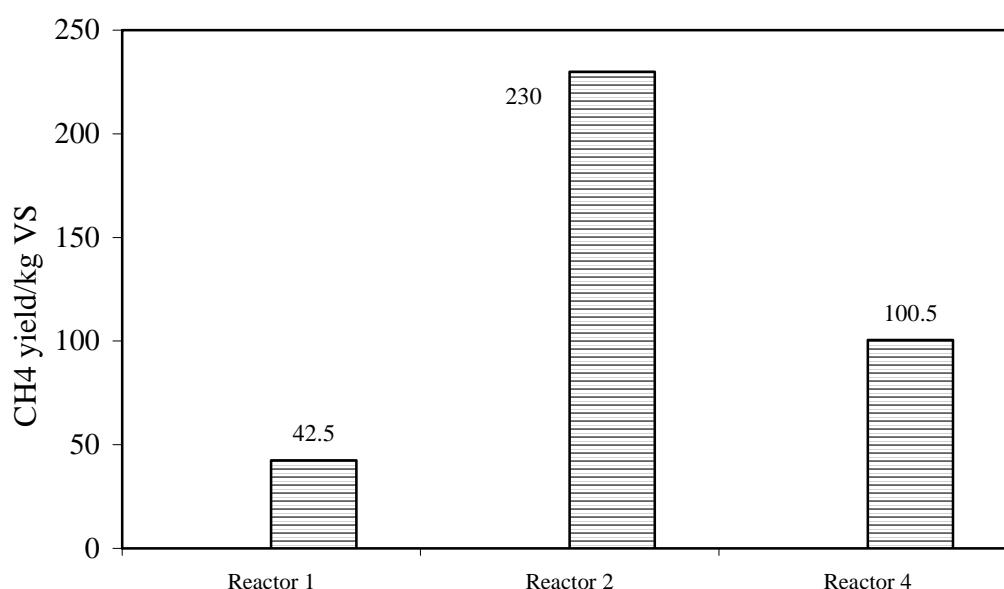


Figure 4.8 Specific methane production in R1, R2 and R4

After 96 days of experiment, the total methane yields were 230L/kg VS (Table A-2a) in reactor R2, while only 42.5 L/kg VS (Table A-1a) in reactor R1. The total methane yields in R4 after 45 days operation was 100.47 L/kg VS (Table A-3a). The higher amount of

biogas yield in reactor R2 was well corresponding to the lower COD concentration at the end of experiment. In addition, daily biogas production was very sensitive to the fluctuation of ambient temperature and profoundly affected by the seasonal change of ambient temperature.

The specific methane yield measured the total amount of methane produced per unit of the initial concentration of TVS in the mixture of wastes. The results for the specific methane yield was illustrated in figure 4.8 for all assays and for an operation time of 96 days and 45 days in run 2. It can also be observed that the assays with a recirculation leachate presented a higher specific methane yield.

Results of this study can also be compared with the results described in the studies of Kim (2003), Griffin (1998). Their experiments involved same types of waste and process, Kim (2003), Griffin (1998) had reached similar value of specific methane yield (240-290m³ CH₄/ton TVS added) while Kayhanian (1995), Callaghan (2002), Bouallagui (2004) and Stroot (2001) achieved values (450-750m³ CH₄/ton TVS added). It can be noticed that the differences upon the composition of different substrates used in each country or type of technology may justify the different values for specific methane yield.

K. Overall SEBAC process assessment

Table 4.2 Overall SEBAC process assessments

Parameter	Unit	R1	R2	R4
Total volume production	(L)	1631	5428	5066
Biogas production/kg VS input	(L)	115.5	384	307
CH ₄ VS in pilot experiment	(L)	42.5	230	100.5
CH ₄ VS in BMP assay	(L)	349.97		
Process efficiency	(%)	12.1	65.7	28.7

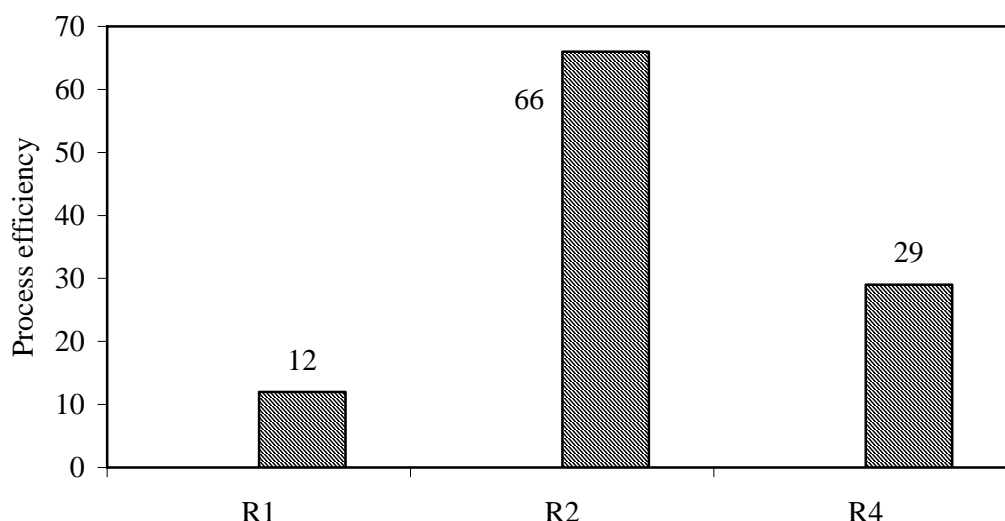


Figure 4.9 Assessment process efficiency of R1, R2 and R4

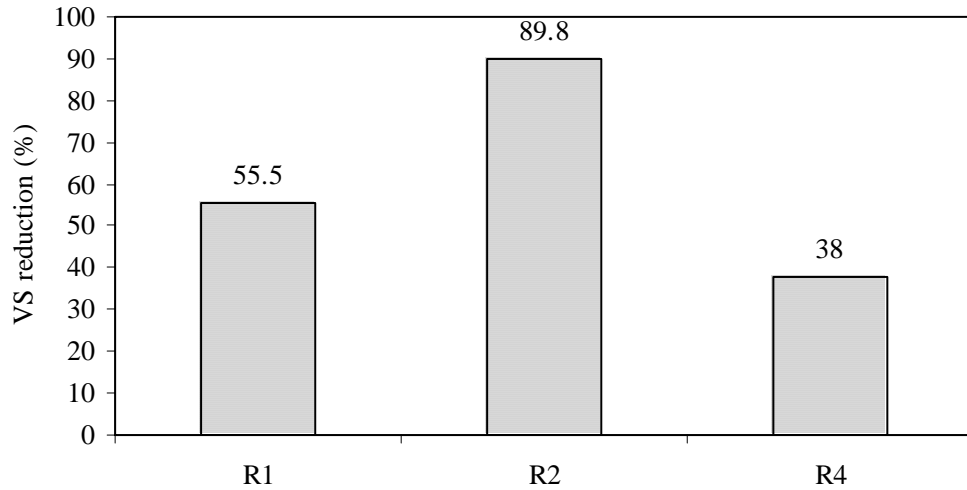


Figure 4.10 Volatile solid reduction (%) of R1, R2 and R4

L. DOC

Anaerobic digestion is a complex biochemical process, in which organic compounds are mineralized to biogas, consisting primarily of methane and carbon dioxide, through a series of reactions mediated by diverse anaerobes. Under balanced operation, the rate of production of intermediates is matched by their rate of consumption. However, disturbances such as an increase in the concentration of organic compounds in the feed (organic overload) can cause an imbalance in the process (Switzenbaum et al., 1990), resulting in the accumulation of volatile organic acid, especially propanoic acid (Gujer et al., 1983). Numerous observations of anaerobic digestion of wastes suggest that a high concentration of volatile organic acids has a direct correlation with digester performance. Propanoic acid levels have been found to rise prior to failure of digesters treating swine wastes (Fischer et al., 1981), municipal sludge (Kaspar et al., 1978), and food processing wastes (van den Berg et al., 1978).

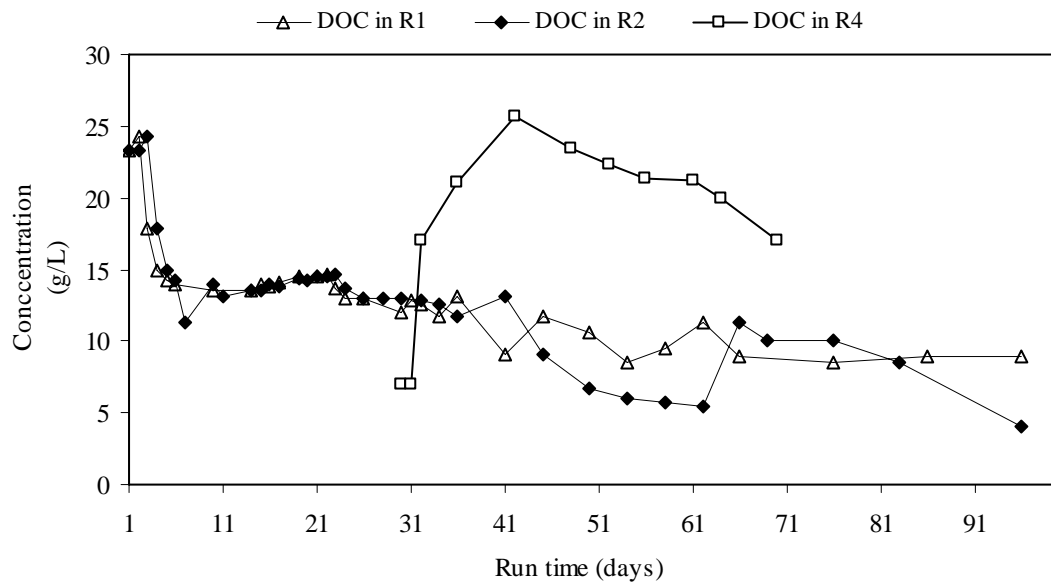


Figure 4.11 Trend DOC concentration in R1, R2 and R4

The temporal evolution of the DOC leachate concentrations and the DOC in R1, R2 and R4 were shown in figure 3.4. The initial DOC concentrations were 20 (Table B-1a), 23.3 (Table B-1b) and 7g DOC/L (Table B-1c) for R 1, R2 and R4, respectively.

From the figure 4.11, initial DOC concentrations increased in the first few days and then decreased until the day 6 and were almost stable from day 12 to day 22 after feeding. It meant that solid waste of AIT campus used in this study campus had large percentage of food wastes, it is comprised of fruits and vegetables containing simple and complex carbohydrates, both soluble and insoluble sugars are readily available. The dissolution of the soluble components of the waste probably led to the increase in the DOC concentration during the first few days. A similar trend was observed in the study of Part (2001). Subject of his study was a slurry-phase in decomposing food waste. Part (2001) demonstrated that the increase of DOC at the beginning of decomposition of food waste may be due to the dissolution of the soluble components such as sugars.

After 19 days the DOC concentrations in R1, R2 and R4 were 14.1, 14.4 and 25.7 g , it implied that waste decomposition was faster in R4.

M. BMP test

The methane yield is limited by the biodegradability of type of solid waste and depends on digester design. BMP test is indicator used for evaluate the performance of the anaerobic digestion process.

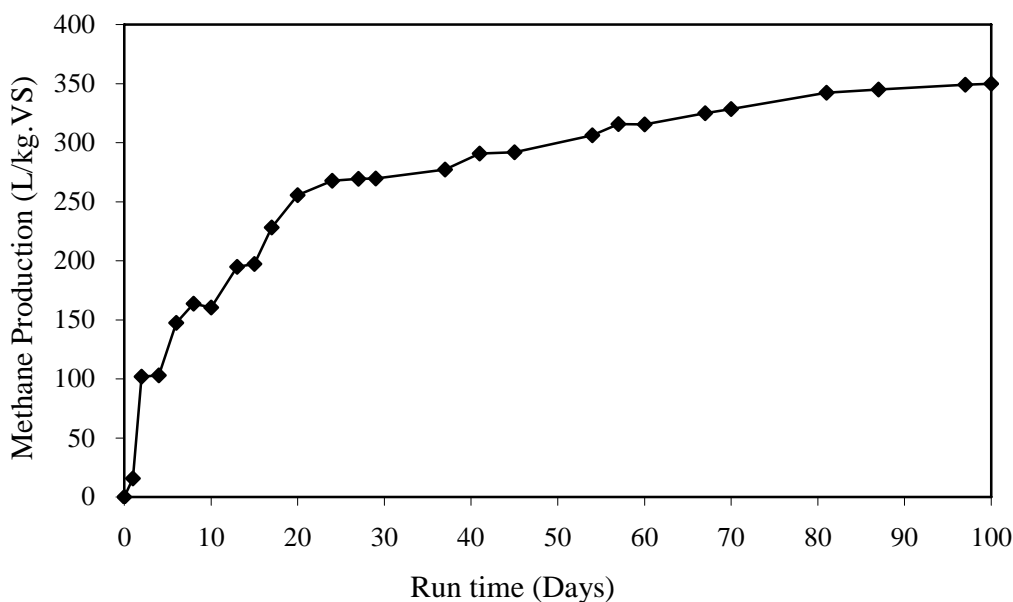


Figure 4.12 Cumulative daily biogas production in BMP test

The BMP test were performed on mesophilic temperature (37°C). Detail procedure was mentioned in chapter 3. The test was performed in favorable environmental condition for the microorganisms such as pH, and temperature. Thus the test was used determined maximum methane volume could be obtained from amount of volatile solid.

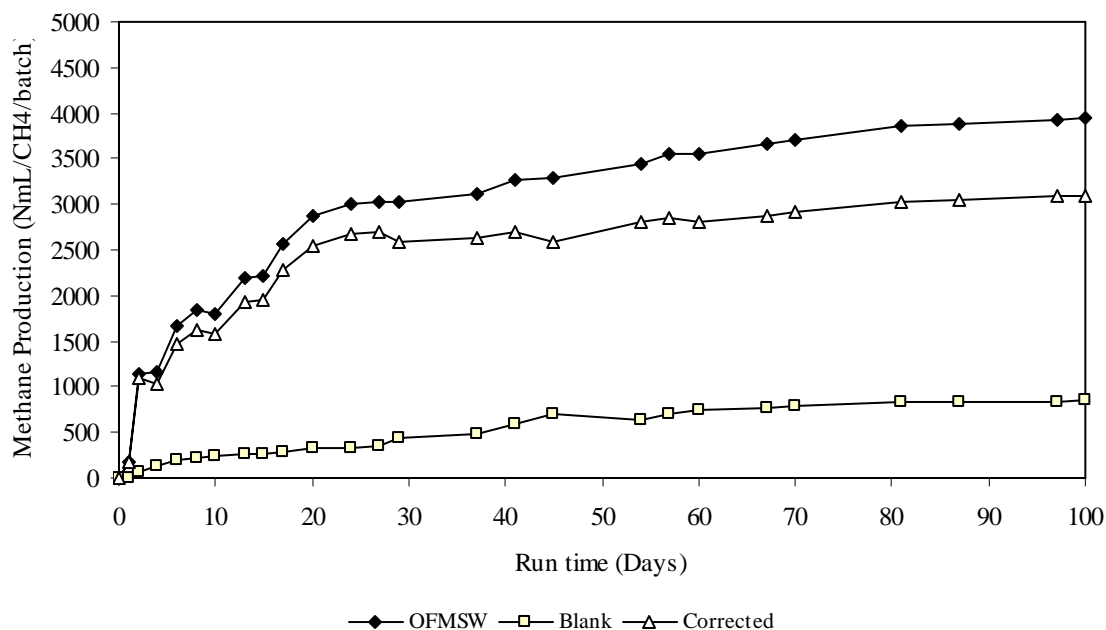


Figure 4.13 Cumulative volume productions in lap scale

The test was conducted on substrate and blank. Figure 4.12 and 4.13 presented the gas production from 6 lab-scale reactors, triplicate blank reactors and triplicate waste reactor. The blank sample included water and inoculums represent the gas production produced by the inoculum itself. The methane production from the inoculum was subtracted from methane production of the waste samples to get the corrected value of methane potential.

The final results after 100 days of mesophilic incubation showed that for each kg VS of the fresh waste, around 349 L of methane (Table C-1, 2, 3, 4, 5, 6) could be produced.

4.2 Post treatment with windrow composting

A. Introduction

During anaerobic digestion of organic wastes in biogas reactors, microorganisms convert most of the carbon in the waste to biogas (methane and carbon dioxide), while the plant nutrients are retained in a digestate that can be used as a fertiliser on agricultural soil. the studies of Deboz (2002) showed that application of such digestate reduces the need for artificial fertilisers, improves the physical and chemical properties of the soil and enables a recycling of nutrients. Application to the land of biosolids derived from anaerobic digestion processes is the most attractive option in terms of environmental issues. This is because of the recovery of nutrients attained and the attenuation of the loss of organic matter suffered by soils under agricultural exploitation.

However, before digestate can be accepted as a fertilising agent, its content of pollutants must be below levels that may pose a risk to the environment or to human health.

Angelidaki (2000) demonstrated that the amount of organic pollutants in digestate is affected by general factors, such as feedstock composition and process management. Donovan (1992) showed that effectively, application of biosolids to the land requires them

to be stabilized. The study of Tchobanoglous (1995) demonstrated that the three principal objectives of stabilization are the reduction of pathogens, the elimination of unpleasant smells, and decreasing or eliminating the potential for putrefaction.

The digested waste from R1, R2 and R3 was cured for two weeks by windrow compost. The aim of the present work was to evaluate composting of the digested waste of three reactors. Table 4.2 presents the results of ultimate and proximate analyses for the various types of waste used in this study.

Table 4. 3 Unloading data for digesters

Parameter	Digested sludge from R1	Digested sludge from R2	Digested sludge from R3	Optimum Condition (EPA, 1994)
Nitrogen (% w)	1.8-2	1.8-1.9	1.8-1.9	1
Volatile solid (% w)	68	60	53	
pH	7.8	8.1	8.3	7-7.5
Moisture (% w)	60	78	78	50-55%
C/N	19	17	15	20-25
P (% w)	0.58	0.54	0.51	1

B. pH

From figure 4.13 it was observed that the temperature gradient has a direct effect on the pH level in the compost pile. The initial pH of digested compiles were alkaline, ranging between 7.8 and 9. The pH values of the composting materials then increased gradually due to an increase in NH_3 generated by the biochemical reactions of nitrogen-containing materials. Theoretically, the composted products should have a neutral pH value during the final stage of stability (Li and Jang et al., 1999).

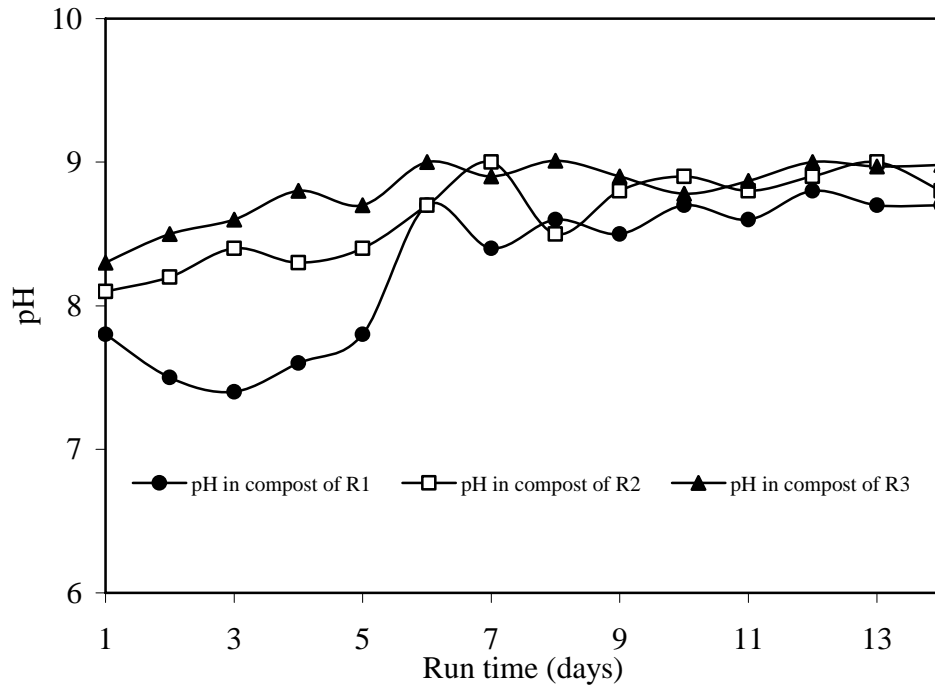


Figure 4.14 pH profile during the windrow composting pile

C. Temperature

According to Barton (1979), microbial decomposition during composting releases large amounts of energy as heat due to the biological oxidation of carbon and, therefore, temperature is a good process indicator. The three composting piles did not achieve thermophilic temperatures ($>45^{\circ}\text{C}$) in two weeks. We observed that not significant different the temperature profile during the first two week (figure 4.15). The temperature rise directly affects degradation of organic matter into smaller fractions through bacterial respiration. It also explains the active consumption of soluble organic fractions Epstein et al (1997) and the dominance of thermophilic organisms in the pile, which would then break down the larger organic particles.

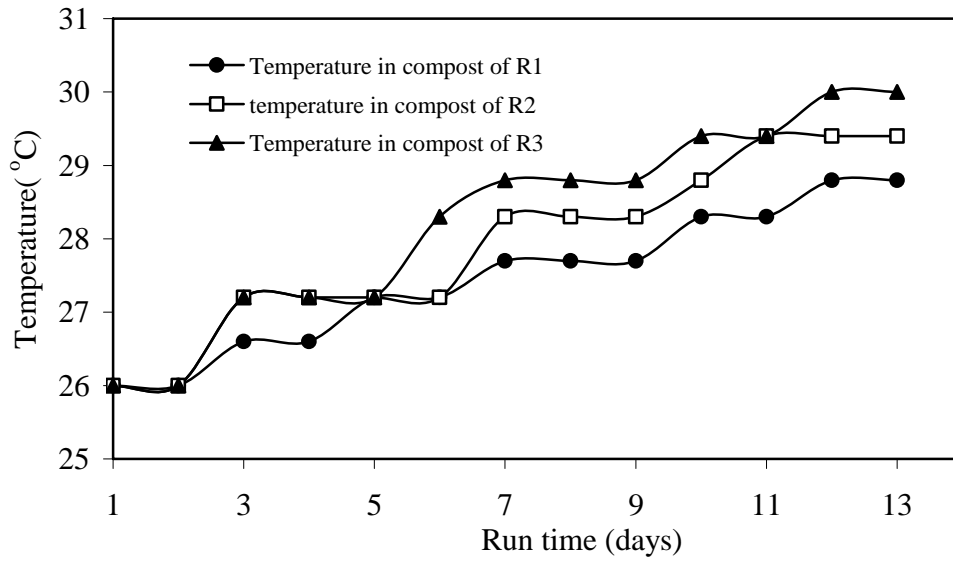


Figure 4.15 Temperature profile during the composting

Table 4.3 shows that the moisture content of R1 dropped dramatically to below 46 % on day 14. In contrast, moisture content in R2 and R3 reactor steady remain 55% and 49 respectively. The trends of temperature showed that there were not clearly evident that three compost piles cures in two weeks.

Table 4.4 Quality of composting

Parameter	Compost of R1	Compost of R2	Compost of R3
Nitrogen (%w)	1.8	1.74	1.65
Volatile solid (% w)	62	55	49
pH	8.7	8.8	8.98
Moisture (%w)	46	56	57
C/N	19	17	15
P (%w)	0.54	0.53	0.52

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This study was conducted on anaerobic treatment of OFMSW. SEBAC experiments were conducted in pilot scale reactors. Since a stabilized reactor was used to start up the SEBAC system the need for pre-stage operation was eliminated. Three cycles of SEBAC experiments were performed with no circulation, direct circulation and exchange leachate between new reactor and old reactor. Higher biogas production in relatively shorter digestion period was obtained under ambient condition. The following conclusions are drawn based on the observed result.

A. The Anaerobic digestions operated in no circulation leachate and circulation leachate.

- Reactor R1 and Reactor R2. Circulation of leachate within reactor produced about 5 time more methane than the no circulation reactor, indicating that leachate circulation has a positive effect on methane recoveries. These experimental results are in a agreement with previous reports, Kim (2003), Griffin (1998). The results of experiment also indicated that the leachate recirculation leachate appeared to be beneficial in maintaining high methane composition generated. The propagation of methane producing bacteria was promoted with the leachate recycle and this promotion was further enhanced by adjusting the leachate recirculation rate.
- Biogas production was strongly dependant on and very sensitive to the fluctuation of ambient temperature.
- Leachate recirculation decreases the amount of the discharged leachate in anaerobic landfills.
- The positive effect of leachate recirculation is more clearly in anaerobic digestion than no circulation leachate. Leachate recirculation is an emerging technology for management of leachate and enhancement of waste stabilization. The optimal recirculation rate and the appropriate design of a recirculation system appropriate for organic-rich waste. After recirculation, ammonia nitrogen and some persistent organic compounds can be accumulated in the effluent leachate. This leachate is more suitable for physical-chemical treatment methods (e.g., chemical precipitation, advanced oxidation , etc.).
- The specific methane yield as obtained with in three SEBAC reactors are 42, 230 and 100 L CH₄ /kg VS in 96 days and 45 days operation, respectively with the no circulation leachate reactor, direct circulation reactor and exchange leachate reactor. These values correspond to the 12%, 66%, 29 % process efficiency calculated based on the laboratory BMP assay.
- The results of this study in run 1 showed that the COD concentrations in leachate are very high. However, landfilled municipal solid wastes can be treated by introducing leachate into the biodegradable waste. If too much leachate is recirculated problems such as acidic conditions may occur.

- The results of this study showed the feasibility of leachate recirculation in reducing the overall leachate loading for treatment and in enhancing the degradation of solid waste. The leachate recirculation should be projected by the landfill managers as an effective measure in increasing the potential filling capacity of a landfill site.

B. The Anaerobic digestion operated in exchange leachate.

- Reactor R4. exchange leachate methane generation rate remained low in the initial digestion phase until pH reached neutral at day 27, where upon methane production increased significantly. The results of experiment also indicated that sequential batch operation investigated here overcomes the disadvantages of a batch reactor by successfully starting a digester by inoculation with leachate. Once conditions are achieved, where the microorganisms are acclimatized to the environment in a fresh-waste bed, the start-up period is dramatically reduced to just a few days. The traditional biogas production curves which showed erratic biogas generation from landfilled MSW become more uniform and steady. The results also showed that this process was very effective in converting high concentrations of VFAs produced in start-up reactors to methane in mature reactors. By increasing the leachate exchange rate between mature and start-up reactors, the time to reach methanogenesis in start-up reactors decreased markedly. As a result a greater number of batches of waste may be digested in a shorter time frame, leading to overall increased methane productivity.
- Exchange leachate is a very feasible method for small pilot leachate treatment as an effective way to enhance the microbial decomposition of biodegradable solid wastes for stabilization, as in the municipal solid waste collected from household of AIT campus. For practical purposes, the results presented in this study can be extended to anaerobic solid waste pilot bioreactors.

C. Post digestate

- Post-treatments are necessary if anaerobic effluents need to be discharged into land, because anaerobic digestion alone is not able to produce effluents that can meet the discharge standards applied in most industrialized countries, particularly for COD and nitrogen.
- The anaerobic digestion end products are fairly stable residues. The percentage of nitrogen and phosphorus in the digestate shows that anaerobic digestion does not reduce nitrogen and phosphorus but keeps the value of nutrients intact for fertilizer. It meets the Thai guideline proposed by Land Development Department Calorific value analysis showed that it has potential to be used as RDF also.
- Based on results from the laboratory investigation, there is a little cause of concern from heavy metal contamination. All heavy metal concentration fell below the WHO standard (proposed, 1997) of compost for developing countries.

5.2 Recommendations

The SEBAC anaerobic digestion of OFMSW, proved to be viable options not only for mass/volume reduction of the waste but also for production of bio-energy and economic byproducts. However, state of art is still deficient and much remains to be done. The following recommendations are made for further research.

- The Anaerobic digestion should further investigate on effect of indirect circulation in SEBAC
- The solid residue after digestion is mainly composed of hard to degradable materials which are rich in lignin (fibrous matter). In this study, we operated windrow composting for treat solid residue in two weeks. The stabilized digested waste was not seen clearly cured after two week .
- Organic matter is essentially composed of cellulose, lignin and hemicelluloses which have different intrinsic biodegradability. Investigation on contents of these compounds can be conducted to evaluate maximum theoretical quantity of biodegradable organic matter and stability of the waste in stabilized waste.
- To study the nitrogen transformations during the pretreatment of municipal solid waste by windrow composting.

References

- Angelidaki, I., Mogensen, A.S. and Ahring, B.K. (2000). Degradation of organic contaminants found in organic waste, *Biodegradation* 11, 377–383.
- Angelidaki, I. (2002). Anaerobic biodegradability of macro pollutants. Workshop on harmonization of anaerobic biodegradation, activity and inhibition assays. Lago d'Orta, Italy. URL: <http://www.ftns.wau.nl/mt/abai/Angelidaki.pdf>
- Baere L. (2000). Anaerobic digestion of solid waste: state-of-the-art. *Water Science and Technology*, 41(3):283-90.
- Berge, N.D and Reinhart, D.R. (2006). In situ ammonia removal in bioreactor landfill leachate, *Waste Management* 26, 334–343.
- Barlaz, M.A., Milke, M.W., Ham, R.K. (1987). Gas production parameters in sanitary landfill simulators. *Waste Management Research* 5, 27–39.
- Bernal, O. , P. Llabres, F. Cecchi and J. Mata-Alvarez (1992) A Comparative Study of the Thermophilic Biomethanization of Putrescible Organic Wastes, *Odpadny vody / Wastewaters*, 1(1), 197-206.
- Bae, J.H., Cho, K.W., Bum, B.S., Lee, S.J., and Yoon, B.H. (1998) Effects of leachate recycle and anaerobic digester sludge recycle on the methane production from solid waste. *Water Science Technology*. 38(2), 159–168.
- Bjornsson, L., M. Murto, and B. Mattiasson. (2000). Evaluation of parameters for monitoring an anaerobic co-digestion process. *Applied Microbiology Biotechnology* 54: 844-849.
- Bouallagui, H., Torrijos, M., Godon, J.J., Molleta, R., Ben Cheikh, R. and Touhami Y. (2004). Two-phase anaerobic digestion fruit and vegetable wastes: bioreactors performance, *Biochemical Engineering Journal* 21, pp. 193–197.
- Burton, S.A.Q and Watson-Craik, I.A. (1998). Ammonia and nitrogen fluxes in landfill sites: applicability to sustainable landfilling, *Waste Management and Research* 16(1), 41–53.
- Barton, A.F.M. (1979). Resource Recovery and Recycling, Wiley, USA .
- Callaghan, F.J., Wase, D.A.J., Thayanithy, K. and Forster, C.F. (2002). Continuous codigestion of cattle slurry with fruit and vegetable wastes and chicken manure, *Biomass and Bioenergy* 27, 71–77.
- Chandler, J.A., Jewell, W.J., Gossett, J.M., Soest, P.J. van, and Robertson, J.B. (1980). Predicting methane fermentation biodegradability. *Biotechnology & Bioengineering Symposium* 10, 93-107.
- Chan, G.Y.S., Chu, L.M., Wong, M.H., (2002). Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment. *Environmental Pollution* 118, 393–399.

Cecchi F, Pavan, P. and Mata-Alvarez, J.(1997). Kinetic study of thermophilic anaerobic digestion of the fresh and pre and pre-composted mechanically selected organic fraction of MSW. *Journal Management Science and Health A32* (1), 195-213.

Chen, H., Ecke, H., Kylefors, K., Bergman, A., Lagerkvist, A., (1995). Biochemical methane potential (BMP) assays of solid waste samples. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.), Fifth International Landfill Symposium, 2–6 October 1995, Cagliari, Italy. *CISA* 1(3), 615–627.

Christensen, T.H., Kjeldsen, P. (1989). Basic biochemical processes in landfills. In Christensen, T.H., Cossu, R., Stegmann, R. (Eds), Sanitary Landfilling: Process, Technology and Environmental Impact. *Academic Press*, London, 29-49.

Chugh S., Chynoweth, D.P., Clarke W., Pullammanappallil, P. & Rudolph, V. (1999). Degradation of unsorted municipal solid waste by a leach-bed process. *Bio-resource Technology*, Volume 69, Number 2,, 103-115.

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

Chugh, S., Chynoweth, D.P, Clarke, W., Pullammanappallil, P., and Rudolph, V. (1998). Degradation of unsorted municipal solid waste by a leach-bed process. *Bioresource Technology*, 69, 103-115.

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

Chynoweth, D.P, Sifontes, J.R. & Teixeira, A.A. (2003). Sequential batch anaerobic composting of municipal and space mission wastes and bioenergy crop. In the Proceedings of ORBIT 2003 conference, Perth, Australia, 317-326.

Epstein, E. (1997). The Science of Composting, Technomic Publishing Company, Lancaster, PA, USA.

Dearman B. and Bentham R.H. (2007). Anaerobic digestion of food waste: Comparing leachate exchange rates in sequential batch systems digesting food waste and biosolids. *Waste Management*. 27(12), 1792-1799

Debosz, K., Petersen, S.O., Kure, L.K. and Ambus, P. (2002). Evaluating effects of sewage sludge and household compost on soil physical, chemical and microbiological properties, *Apply Soil Ecology* 19, 237–248.

Donovan, J.F. 18 May (1992). Developments in wastewater sludge management practices in the United States, *Proceedings of the Paper Presentation at the New Developments in Wastewater Policy, Management, Technology Conference* Sydney, Australia.

Farquhar, G.J and Rovers, FA. Rovers. (1973). Gas production during refuse composition, *Water, Air and Soil Pollution* 2, 483–495.

Fujishima, S., Miyahara, T and Noike, T. (2000). Effect of moisture content on anaerobic digestion of dewatered sludge: ammonia inhibition to carbohydrate removal and methane production. *Water Science Technology* 41, 119–127.

Fischer, J.R., Ianotti, E.L and Sievers, D.M. (1981). Anaerobic digestion of swine manures at various influent solids concentration, *Agriculture Wastes* 6, 157–166.

Ghosh, S. (1985). Solid-Phase Methane Fermentation of Solid Waste. *Journal of Energy Resources and Technology*, 107, 402-406.

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

Ghosh, S. (1985). Solid-Phase Methane Fermentation of Solid Waste. *Energy Resources and Technology*, 107, 402-406.

Gotaas, H.B. (1956). Composting: Sanitary Disposal and Reclamation of Organic Wastes, *Monograph Series* No. 31, World Health Organization, Geneva (1956).

Griffin, M.E., McMahon, K., Mackie, R and Raskin, L. (1998). Methanogenic population dynamics during start-up of anaerobic digesters treating solid waste and biosolids, *Biotechnology & Bioengineering* 57 (3), 342–355.

Gunasekera, L.S.W., Mannapperuma, N.R.C., Basnayake B.F.A. & Somathilaka, W.E.G. (2004). Evaluation of different methods of composting as pre-treatment of MSW for landfilling. In *Proceedings APLAS, 3rd Asia Pacific Landfill Symposium*, Kitakyushu, Japan, 207-212.

Gujer, W. and Zehnder, A.J.B. (1983). Conversion processes in anaerobic digestion, *Water Science Technology*. 15, 127–167.

Hartmann, H., and B. K. Ahring. (2005). Anaerobic digestion of the organic fraction of municipal solid waste: influence of co-digestion with manure. *Water Research (ISSN)* , 39 (8), 1543-1552.

Hartmann, H., and B. K. Ahring. (2006). Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. *Water Science and Technology*. 53 (8), 7-22.

Hartman, H., Moller, B.H. & Ahring, K.B. (2004). Efficiency of the anaerobic treatment of the organic fraction of municipal solid waste: collection and pretreatment. *Waste Management & Research*, 22, 35-41.

Hartmann, H., I. Angelidaki, I., and B. K. Ahring. (1999). Increase of anaerobic degradation of particulate organic matter in full-scale biogas plants by mechanical maceration. In: Mata-Alvarez, J., A. Tilche, A., and F. Cecchi (Eds.), *Proceedings of the*

Second International Symposium on Anaerobic Digestion of Solid Wastes, Barcelona, 1(92), 129-136.

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.

Iglesias, J.R., Pelaez, C.L., Maison, E. and Andres, H.S. (2000). A comparative study of the leachates produced by anaerobic digestion in a pilot plant and at a sanitary landfill in Austrias, Spain. *Waste Manage Research* .18, 86–93.

Inanc, B. S., Matsui and Ide, S. (1996). Propionic acid accumulation and controlling factors in anaerobic treatment of carbohydrate: effects of hydrogen and pH, *Water Science Technology* 34, 317–325.

Jokela,J., Kettunen, R.H., Sormunen, K.M., and Rintala,J.A. .(2002). Biological nitrogen removal from municipal landfill leachate: low-cost nitrification in biofilters and laboratory scale in-situ denitrification. *Water Research*. 36, 4079–4087.

Karlsson, I., and J. Goransson. (1993). Thermic sludge treatment. *Water Science and Technology*. 27 (5-6), 449-456.

Kayhanian , M. and Rich, D. (1995). Pilot-scale high solids thermophilic anaerobic digestion of municipal solid waste with an emphasis on nutrient requirements, *Biomass and Bioenergy* 8 (6), 433–444.

Kim, J., and C. Park. (2003). Effects of various pretreatments for enhanced anaerobic digestion with waste activated sludge. *Bioscience & Bioengineering*. 95 (3), 271-275.

Kim, J., C. Park, T. K. Kim, M. Lee, S. Kim, S. W. Kim, and J. Lee. 2003. Effects of various pretreatments for enhanced anaerobic digestion with waste activated sludge *Japan Bioscience & Bioengineering* 95 (3), 271-275.

Kim, H.W., Han, S.K and. Shin, H.S. (2003). The optimization of food waste addition as a co-substrate in anaerobic digestion of sewage sludge, *Waste Management Research* 21, 515–526.

Kinman, R.N. Nutini, Walsh, D.L. Vogt,W.G. Stamm,J.J, J. Rickabaugh, J. (1987). Gas enhancement techniques in landfill simulators. *Waste Management and Research* 5, 13–25.

Kolsch, F. and Ziehmman, G. (2004). Landfill stability risk and challenges. URL: <http://www/Jxj.com/wmw/index.html>.

Koster,I.W. and Lettinga, G. (1984). The influence of ammonium-nitrogen on the specific activity of pelletized methanogenic sludge. *Agriculture Wastes* 9, 205–216.

Kyelefors, Andreas K., L., and Lagerkvist, A., 2003. A comparison of small –scale, pilot scale and large-scale tests for predicting leaching behaviour of landfilled wastes. *Waste management*, 23: 45-59.

Kaspar, H.F and Wuhrmann, K. (1978). Production inhibition in sludge digestion, *Microbiol. Ecol.* 4, 241–248.

Kruempelbeck, I., and Ehrig, H.J. (1999).Long term behaviour of municipal solid waste landfills in Germany. In: T.H. Christensen, R. Cossu and R. Stegmann, Editors, *Proceedings of the seventh international waste management and landfill symposium* Sardinia, Italy, CISA Publisher, 27–36.

Komilis, D.P., Ham, R.K., Stegmann, R. (1999). The effect of landfill design and operation practices on waste degradation behavior: a review. *Waste Management and Research* 17, 20–26.

Lay, J.J. Li, Y.Y., Noike, T., Endo., J., and Ishimoto, S. (1997). Analysis of environmental factors affecting methane production from high-solids organic waste. *Water Science and Technology*, 36, 6-7, 493-500.

Li, G.S and Jang, F.S. (1999). The solid waste composting and the organic compound fertilizer is produced, Chemical industry publishing Co., Beijing, China.

Ledakowicz, S., and Kaczarek, K. (2002).Laboratory simulation of anaerobic digestion of municipal solid waste, *ISWA 2002 world environmental congress, appropriate environmental and solid waste management and technologies for developing countries* Istanbul, Turkey , 1139–1146.

Ludwig, C., Hellweg, S., and Stucki S. (2003). Municipal solid waste management: strategies and technologies for sustainable solutions. Springer. ISBN: 3-540-44100-X URL: <http://msw.web.psi.ch/>

Mata-Alvarez, J. (2003). *Biomethanization of the Organic Fraction of Municipal Solid Wastes*. IWA Publishing. ISBN: 1- 900222 -14-0.

Mata-Alvarez, J., S. Mace, and P. Llabres. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology*. 74, 3-16.

Mata-Alvarez, J., & Sans, C. (1995). Volatile fatty acid production by mesophilic fermentation of mechanically-sorted urban organic wastes in a plug-flow reactor. *Bioresource Technology*, 5, 89-96.

Mata-Alvarez, J., Mace, S. & Llabres, P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology*, 74, 3-16.

McCarty, P.L. (1964). Anaerobic waste treatment fundamentals: environmental requirements and control. *Public Works* 95, 123.

Mohee, R., and Ramjeawon, T. (2003). Appropriateness of the sequential batch anaerobic composting (SEBAC) technology as a treatment method for organic waste in Mauritius. *Proceedings of ORBIT* 2003, 341-350.

New Zealand Eng. (1951). Second Interim Report of the Inter-departmental Committee on utilization of Organic Wastes.

O'Keefe, D.M., Chynoweth, D.P., Barkdoll, A.W., Nordstedt, R.A., Owens, J.M and Sifontes, J. (1993). Sequential batch anaerobic composting of municipal solid waste (MSW) and yard waste. *Water Science and Technology*, 27, 2, 77-86

O'Keefe, D.M., and Chynoweth, D.P. (1999). Influence of phase separation, leachate recycle and aeration on treatment of municipal solid waste in simulated landfill cells. *Bioresource Technology*, 72, 55-66.

Onay, T.T. and Pohland, F.G. (1998). In situ nitrogen management in controlled bioreactor landfills, *Water Research* 32 (5), 1383-1392.

Onay, T.T and Pohland, F.G. (2001). Nitrogen and sulfate attenuation in simulated landfill bioreactors, *Water Science and Technology* 44 (2-3), 367-372.

Ouedraogo, A. (1999). Pilot scale two-phase anaerobic digestion of the biodegradable organic fraction of Bamako district municipal solid waste. In *II. Int. Symp. Anaerobic Digestion Solid Waste*, held in Barcelona, June 15-17, 1999 (eds. J. Mata-Alvarez, A. Tilche and F. Cecchi), 2, 73-76.

Polprasert, C. (1996). *Organic waste recycling technology and management*. John Wiley & sons. ISBN 0-471-96434- 4.

Paulo, P.L., Villa, G. B., Van Lier and Lettinga, G. (2003). The anaerobic conversion of methanol under thermophilic conditions: pH and bicarbonate dependence, *Journal Bioscience Bioengineering* 96, 213-218.

Park, J.I., Yun, Y.S and Park, J.M. (2001). Oxygen-limited decomposition of food wastes in a slurry bioreactor, *J. Ind. Microbiology Biotechnology*, 27, 67-71.

Pfeffer, J.T. (1979). Anaerobic Digestion Processes. In Stafford, D.A., Wheatley, B.I., and Hughes, D.E. Anaerobic Digestion 15-33. London: *Applied Science Publishers Ltd*.

Rodhe, H. (1990). A Comparison of the contribution of various gases to the greenhouse effect. *Science*, 248, 1217-1219.

Price, G.A., Barlaz, M.A and Hater, G.R. (2003). Nitrogen management in bioreactor landfills, *Waste Management* 23, 675-688.

Pohland, F.G., and Kang, S.J. (1974). Sanitary landfill stabilisation with leachate recycle and residual treatment. In: *AIChE Symposium Series. Water, II: Municipal Waste Treatment*, 308–327.

Pohland, F. G., Harper, S. R. (1987). Retrospective Evaluation of the Effects of Selected Industrial Wastes on Municipal Solid Waste Stabilization in Simulated Landfills. EPA/600/S2-87/044. USEPA., 6.

Quasim SR, Chiang W. Sanitary landfill leachate. (1994). USA: Technologic Publishing Company; . ISBN 1-56676-129-8.

Rao, M.S., Singh, S.P., Singh, A.K. & Sodha, M.S. (2000). Bioenergy conversion studies of the organic fraction of MSW: assessment of ultimate bioenergy production potential of municipal garbage. *Applied Energy*, 66, 75-87.

Reinhart, D., and Al-Yousfi, A.B. (1996). The impact of leachate recirculation on municipal solid waste landfill operating characteristics. *Waste Manage. Res.* 14 , pp. 337–346.

Rodhe, H. (1990). A Comparison of the contribution of various gases to the greenhouse effect. *Science*, 248, 1217-1219.

Robinson, H.D., and Maris, P.J. (1979) Leachate from domestic waste: generation, composition and treatment. In: *A review Water Research Centre, UK, Technical Report TR 108* (1979).

Ruskin, F.R., (1982). Food, Fuel, and Fertilizer from Organic Wastes. National Academy Press, Washington.

Sanders, W.T.M., Geerink, M., Zeeman, G., and Lettinga, G. (2000). Anaerobic hydrolysis kinetics of particulate substrates. *Water Science and Technology*, 14(3), 17-24.

San and T. Onay., (2001) Impact of various leachate recirculation regimes on municipal solid waste degradation. *Journal Hazard Matter*, B87, 259–271.

Speece, R.E.(1996). Anaerobic biotechnology for industrial wastewaters, Archae Press, Nashville, TN, USA , 222–26.

Stroot, P.G., McMahon, K.D., Mackie, R.I. and Raskin, L. (2001). Anaerobic co-digestion of municipal solid waste and biosolids under various mixing conditions-I. Digester performance, *Water Research* 35 (7), 1804–1816.

Switzenbaum, M.S., Giraldo-Gomez, E and Hickey, R.F. (1990). Monitoring of the anaerobic methane fermentation process, *Enzyme Microbiology Technology*, 12, 722–730.

Tchobanoglous. G. (1993). *Integrated solid waste management : engineering principles and management issues* / Hilary Theisen and Samuel Vigil. New York : McGraw-Hill.

Tchobanoglous, G. and Burton, F.L. (1995). Ingeniería Sanitaria Tratamiento, evacuación y reutilización de aguas residuales, Metcalf & Hedí Inc., McGraw-Hill/Interamericana de España, SA.

Tong , X.,Smith,L.H., McCarthy, P.L (1990) Methane fermentation of selected lignocellulosic material. *Biomass* 21, 239-255.

United States Environmental Protection Agency, USEPA (1995). *Decision makes guide to solid waste management*, second edition, EPA530-R-95-023, Environmental Protection Agency, Office of Solid Waste, RCRA Information Center, Washington, D.C.

United States Environmental Protection Agency (2004) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002. EPA report # EPA 430-R-04-003. US EPA, Washington, DC.

U.S. Environmental Protection Agency. (1994). *Composting Yard Trimmings and Municipal Solid Waste*. Washington, D.C.: U.S. Environmental Protection Agency. EPA530-R-94-003.

Vandevivere, P., L. De Baere, and W. Verstraete. (2002). Types of anaerobic digester for solid wastes. In J. Mata-Alvarez (Ed). *Biomethanization of the Organic Fraction of Municipal Solid Wastes*, London: *IWA Publishing*, 111-137.

Vavilin, V. A., M. Y. Schelkanov, L. Y. Lokshina, S. V. Rytov, J. Jokela, and E. Salminen. (2002). A comparative analysis of a balance between the rates of polymer hydrolysis and acetoclastic methanogenesis during anaerobic digestion of solid waste. *Water Science and Technology*. 45 (10), 249-254.

Vavilin, V.A., Rytov, S.V., Pavlostathis, S.G., Jokela, J., and Rintala, J. (2003). A distributed model of solid waste anaerobic digestion: sensitivity analysis. *Water Science and Technology*, 48(4), 147-154.

Vavilin, V.A., Guse, E.M., Pavlostathis, S.G., Jokela, J.P.Y., and Rintala, J. A., (2002). Modeling of solid waste anaerobic digestion: Effects of moisture and leachate recirculation, *Poster Presentation*, 3-60.

Vavilin, V.A., Jonsson, S., Ejlerstson, J., Svensson, B.H. (2006). Modelling MSW decomposition under landfill conditions considering hydrolytic and methanogenic inhibition. *Biodegradation*. Online doi:10.1007/s10532-005-9009-7.

Yuen, S.T.S., Styles, J.R., McMahon, T.A. (1995). An active landfill management by leachate recirculation – a review and an outline of a full-scale project. *In: Proceedings Sardinia 95, Fifth International Landfill Symposium*, 1–17.

van den Berg, L.A and Lentz, C.P. (1977) Anaerobic digestion of pear waste: laboratory equipment design and preliminary results, *J. Can. Inst. Food Technology*. 4, 159–165.

Vieitez, E.R., and Ghosh, S. (1999). Biogasification of solid waste by two-phase anaerobic fermentation. *Biomass and Bioenergy*, 16, 299-309

Veeken, A.H.M. and Hamelers, B.V.M. (2000) .Effect of substrate-seed mixing and leachate recirculation on solid state digestion of biowaste, *Water Science and Technology*, 41(3) 255-262.

Veeken, A.H.M., and Hamelers, B.V.M. (1999a). Effect of temperature on hydrolysis rates of selected biowaste components. *Bioresource technology*, 69(3), 249-254

Veeken, A.H.M., and Hamelers, B.V.M. (1999b). Effect of substrate-seed mixing and leachate recirculation on solid state digestion of biowaste. *Proceedings of the second international symposium on anaerobic digestion of solid wastes*, Barcelona, 1, 92: 15-18

Vieitez, E.R., and Ghosh, S. (1999). Biogasification of solid waste by two-phase anaerobic fermentation. *Biomass and bioenergy*, 16: 299-309
Vieitez, E.R., Mosquera, J., and Ghosh, S. (2000). Kinetics of accelerated solid state fermentation of organic-rich municipal solid waste. *Water science and technology*, 41(3), 231-238

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

Visvanathan C. (2004). Mechanical biological pre-treatment of solid waste prior to landfill, <http://www.seauema.ait.ac.th/download/conference/presentation/keynote/KeynoteVisu.pdf>.

Zurbrügg, C. (2002) "Urban Solid Waste Management in Low-Income Countries of Asia; How to Cope with the Garbage Crisis, Presented for: *Scientific Committee on Problems of the Environment (SCOPE) Urban Solid Waste Management Review Session*, Durban, South Africa.

Wiegant, W.M. and Zeeman, G. (1986). The mechanism of ammonia toxicity in thermophilic digestion of livestock wastes. *Agriculture Wastes* 16, 243–253.

Warith, A., Zekry, W., Gawri, N., (1999). Effect of leachate recirculation on municipal solid waste biodegradation. *Journal of Canada Water Quality Research* 34, 267–280.

Appendixes

Appendix A: Pilot scale experimental runs

Table A-1a: Biogas composition in R1

Run time (Days)	Daily gas production (L)	Cumulative gas production (L) in R1	Biogas composition		Specific cumulative biogas production (L/kg TVS) in R1	Daily methane production in R1(L/VS)
			% CH ₄	% CO ₂		
1	62	62	14.20	85.80	4.4	0.62
2	49	111	17.98	82.02	7.9	0.62
3	80	191	20.49	79.51	13.5	1.16
4	80	271	14.98	85.02	19.2	0.85
5	92	363	14.63	85.37	25.7	0.95
6	91	454	6.98	93.02	32.1	0.45
7	60	514	6.57	93.43	36.4	0.28
8	48	562	7.87	92.13	39.8	0.27
9	25	587	6.74	93.26	41.5	0.12
10	10	597	6.53	93.47	42.2	0.05
11	8	605	6.81	93.19	42.8	0.04
12	2	607	6.87	93.13	42.9	0.01
13	0.1	607.1	7.63	92.37	43.0	0.00
14	1	608.1	7.76	92.24	43.0	0.01
15	1	609.1	8.34	91.66	43.1	0.01
16	1	610.1	21.53	78.47	43.2	0.02
17	1	611.1	9.39	90.61	43.2	0.01
18	1	612.1	10.18	89.82	43.3	0.01
19	0.5	612.6	10.09	89.91	43.3	0.00
20	1.6	614.2	10.76	89.24	43.5	0.01
21	1	615.2	11.57	88.43	43.5	0.01
22	1	616.2	18.36	81.64	43.6	0.01
23	2	618.2	27.40	72.60	43.7	0.04
24	3	621.2	16.90	83.10	44.0	0.04
25	1.9	623.1	18.83	81.17	44.1	0.03
26	1.4	624.5	19.92	80.08	44.2	0.02
27	3	627.5	22.56	77.44	44.4	0.05
28	5.3	632.8	23.95	76.05	44.8	0.09
29	4	636.8	26.54	73.46	45.1	0.08
30	4.5	641.3	27.91	72.09	45.4	0.09
31	5.3	646.6	30.21	69.79	45.7	0.11
32	10	656.6	32.52	67.48	46.5	0.23
33	5.4	662	33.76	66.24	46.8	0.13
34	10	672	34.89	65.11	47.5	0.25
35	9.3	681.3	36.04	63.96	48.2	0.24
36	10	691.3	37.23	62.77	48.9	0.26
37	10.9	702.2	37.23	62.77	49.7	0.29
38	7.2	709.4	37.30	62.70	50.2	0.19
39	10	719.4	39.94	60.06	50.9	0.28
40	13.333	732.733	47.65	52.35	51.8	0.45

Appendix A: Pilot scale experimental runs

Table A-1b: Biogas composition in R1

Run time (Days)	Daily gas production (L)	Cumulative gas production (L) in R1	Biogas composition		Specific cumulative biogas production (L/kg TVS) in R1	Daily methane production in R1(L/VS)
			% CH ₄	%CO ₂		
41	13.40	746.13	47.93	52.07	52.8	0.45
42	17.42	763.55	49.28	50.72	54.0	0.61
43	17.69	781.24	49.99	50.01	55.3	0.63
44	17.89	799.13	48.94	51.06	56.5	0.62
45	17.96	817.09	48.22	51.78	57.8	0.61
46	18.02	835.11	49.46	50.54	59.1	0.63
47	12.66	847.77	50.47	49.53	60.0	0.45
48	13.27	861.04	50.39	49.61	60.9	0.47
49	13.33	874.37	50.67	49.33	61.9	0.48
50	13.67	888.04	50.40	49.60	62.8	0.49
51	15.75	903.78	51.74	48.26	63.9	0.58
52	13.33	917.12	52.78	47.22	64.9	0.50
53	13.40	930.52	52.23	47.77	65.8	0.50
54	12.66	943.18	51.68	48.32	66.7	0.46
55	11.66	954.84	49.91	50.09	67.6	0.41
56	12.73	967.57	54.42	45.58	68.5	0.49
57	20.10	987.67	54.69	45.31	69.9	0.78
58	23.32	1010.98	55.12	44.88	71.5	0.91
59	14.74	1025.72	55.32	44.68	72.6	0.58
60	13.74	1039.46	55.77	44.23	73.5	0.54
61	18.56	1058.02	56.55	43.45	74.9	0.74
62	12.73	1070.75	54.80	45.20	75.8	0.49
63	13.40	1084.15	55.93	44.07	76.7	0.53
64	13.13	1097.28	56.27	43.73	77.6	0.52
65	23.52	1120.80	56.22	43.78	79.3	0.94
66	23.45	1144.25	56.09	43.91	81.0	0.93
67	9.85	1154.10	56.22	43.78	81.7	0.39
68	12.06	1166.16	56.09	43.91	82.5	0.48
69	18.83	1184.98	51.64	48.36	83.8	0.69
70	8.71	1193.69	56.47	43.53	84.5	0.35
71	8.24	1201.93	55.68	44.32	85.0	0.32
72	8.04	1209.97	55.71	44.29	85.6	0.32
73	7.37	1217.34	56.89	43.11	86.1	0.30
74	8.04	1225.38	56.71	43.29	86.7	0.32
75	7.57	1232.96	60.61	39.39	87.2	0.32
76	8.11	1241.06	55.76	44.24	87.8	0.32
77	9.85	1250.91	55.58	44.42	88.5	0.39
78	12.13	1263.04	57.14	42.86	89.4	0.49
79	13.47	1276.51	58.44	41.56	90.3	0.56
80	15.41	1291.92	56.99	43.01	91.4	0.62

Appendix A: Pilot scale experimental runs

Table A-1c: Biogas composition in R1

Run time (Days)	Daily gas production (L)	Cumulative gas production (L) in R1	Biogas composition		Specific cumulative biogas production (L/kg TVS) in R1	Daily methane production in R1(L/VS)
			% CH ₄	% CO ₂		
81	15.41	1307.33	56.47	43.53	92.5	0.62
82	16.28	1323.61	57.18	42.82	93.6	0.66
83	15.28	1338.88	56.35	43.65	94.7	0.61
84	17.55	1356.44	58.66	41.34	96.0	0.73
85	15.75	1372.18	54.53	45.47	97.1	0.61
86	22.04	1394.22	52.70	47.30	98.6	0.82
87	19.50	1413.72	57.26	42.74	100.0	0.79
88	20.10	1433.82	52.68	47.32	101.4	0.75
89	21.37	1455.19	52.68	47.32	103.0	0.80
90	20.64	1475.83	52.68	47.32	104.4	0.77
91	28.14	1503.97	52.68	47.32	106.4	1.05
92	24.59	1528.56	52.68	47.32	108.1	0.92
93	24.05	1552.61	52.68	47.32	109.9	0.90
94	22.71	1575.33	52.68	47.32	111.5	0.85
95	26.73	1602.06	52.68	47.32	113.3	1.00
96	29.48	1631.54	52.68	47.32	115.4	1.10

Appendix A: Pilot scale experimental runs

Table A-2a: Biogas composition in R2

Run time (Days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Specific cumulative biogas production (L/kg TVS)	Daily methane production (L/VS)
			% CH ₄	%CO ₂		
1	71	71	14.4	85.6	5.0	0.72
2	50	121	18.5	81.5	8.6	0.66
3	79	200	17.1	82.9	14.2	0.96
4	122	322	12.9	87.1	22.8	1.11
5	178	500	10.8	89.2	35.4	1.37
6	69	569	7.1	92.9	40.3	0.35
7	49	618	7.0	93.0	43.7	0.24
8	32	650	7.9	92.1	46.0	0.18
9	27	677	6.9	93.1	47.9	0.13
10	4	681	6.5	93.5	48.2	0.02
11	0	681	6.8	93.2	48.2	0.00
12	8	689	6.9	93.1	48.7	0.04
13	4	693	9.4	90.6	49.0	0.03
14	6	699	19.2	80.8	49.5	0.08
15	6.3	705.3	20.2	79.8	49.9	0.09
16	5.7	711	22.1	77.9	50.3	0.09
17	8	719	24.4	75.6	50.9	0.14
18	10	729	24.7	75.3	51.6	0.17
19	10.3	739.3	24.1	75.9	52.3	0.18
20	8.2	747.5	24.7	75.3	52.9	0.14
21	9.8	757.3	26.7	73.3	53.6	0.19
22	18.3	775.6	20.8	79.2	54.9	0.27
23	0	775.6	27.1	72.9	54.9	0.00
24	13.2	788.8	27.9	72.1	55.8	0.26
25	12	800.8	27.8	72.2	56.7	0.24
26	10	810.8	29.1	70.9	57.4	0.21
27	12	822.8	28.3	71.7	58.2	0.24
28	14	836.8	29.5	70.5	59.2	0.29
29	14	850.8	30.7	69.3	60.2	0.30
30	18.3	869.1	32.3	67.7	61.5	0.42
31	12.4	881.5	35.3	64.7	62.4	0.31

Appendix A: Pilot scale experimental runs

Table A-2b: Biogas composition in R2

Run time (Days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Specific cumulative biogas production (L/kg TVS)	Daily methane production (L/VS)
			% CH ₄	%CO ₂		
32	22.5	904	39.0	61.0	64.0	0.62
33	24.5	928.5	41.0	59.0	65.7	0.71
34	27.2	955.7	43.8	56.2	67.6	0.84
35	29.2	984.9	47.9	52.1	69.7	0.99
36	30.2	1015.1	50.0	50.0	71.8	1.07
37	39.1	1054.2	52.1	47.9	74.6	1.44
38	50	1104.2	54.4	45.6	78.1	1.92
39	56	1160.2	55.1	44.9	82.1	2.18
40	45.4	1205.6	57.0	43.0	85.3	1.83
41	57.3	1262.9	60.99	39.01	89.35	2.47
42	69.8	1332.7	64.29	35.71	94.29	3.17
43	76.7	1409.4	64.79	35.21	99.72	3.52
44	66.8	1476.2	71.26	28.74	104.44	3.37
45	69.2	1545.4	72.03	27.97	109.34	3.53
46	63.3	1608.7	71.26	28.74	113.82	3.19
47	71.2	1679.9	71.76	28.24	118.86	3.61
48	90.4	1770.3	72.88	27.12	125.25	4.66
49	97	1867.3	71.60	28.40	132.12	4.91
50	99.3	1966.6	71.75	28.25	139.14	5.04
51	91.5	2058.1	72.41	27.59	145.61	4.69
52	85.6	2143.7	72.04	27.96	151.67	4.36
53	87.2	2230.9	70.48	29.52	157.84	4.35
54	78.8	2309.7	70.27	29.73	163.42	3.92
55	68.2	2377.9	70.08	29.92	168.24	3.38
56	69.8	2447.7	68.41	31.59	173.18	3.38
57	71	2518.7	68.54	31.46	178.20	3.44
58	59	2577.7	67.53	32.47	182.38	2.82
59	58.3	2636.0	68.15	31.85	186.50	2.81
60	63.9	2699.9	70.93	29.07	191.02	3.21
61	51.8	2751.7	72.24	27.76	194.69	2.65
62	46.1	2797.8	68.77	31.23	197.95	2.24

Appendix A: Pilot scale experimental runs

Table A-2c: Biogas composition in R2

Run time (Days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Specific cumulative biogas production (L/kg TVS)	Daily methane production (L/VS)
			% CH ₄	% CO ₂		
63	56.8	2854.6	69.56	30.44	201.97	2.80
64	49	2903.6	68.72	31.28	205.44	2.38
65	75.3	2978.9	67.88	32.12	210.76	3.62
66	57.6	3036.5	68.55	31.45	214.84	2.79
67	72.9	3109.4	68.90	31.10	220.00	3.55
68	82.9	3192.3	69.75	30.25	225.86	4.09
69	75.9	3268.2	69.75	30.25	231.23	3.75
70	63.7	3331.9	70.86	29.14	235.74	3.19
71	87.1	3419.0	67.81	32.19	241.90	4.18
72	63	3482.0	68.43	31.57	246.36	3.05
73	53	3535.0	68.97	31.03	250.11	2.59
74	93.2	3628.2	68.57	31.43	256.70	4.52
75	41.5	3669.7	72.05	27.95	259.64	2.12
76	50	3719.7	71.65	28.35	263.18	2.53
77	39.8	3759.5	70.59	29.41	265.99	1.99
78	66.3	3825.8	68.24	31.76	270.68	3.20
79	110.4	3936.2	67.06	32.94	278.49	5.24
80	75	4011.2	69.02	30.98	283.80	3.66
81	129.3	4140.5	67.90	32.10	292.9	6.2
82	119.4	4259.9	65.85	34.15	301.4	5.6
83	118.9	4378.8	72.29	27.71	309.8	6.1
84	123.6	4502.4	71.95	28.05	318.6	6.3
85	89.8	4592.2	70.73	29.27	324.9	4.5
86	114.2	4706.4	61.96	38.04	333.0	5.0
87	101.2	4807.6	73.17	26.83	340.1	5.2
88	100	4907.6	73.17	26.83	347.2	5.2
89	88.2	4995.8	73.17	26.83	353.5	4.6
90	74.9	5070.7	73.17	26.83	358.8	3.9
91	93	5163.7	73.17	26.83	365.3	4.8
92	68.9	5232.6	73.17	26.83	370.2	3.6
93	60	5292.6	73.17	26.83	374.5	3.1
94	52	5344.6	73.17	26.83	378.1	2.7
95	45.1	5389.7	73.17	26.83	381.3	2.3
96	38.9	5428.6	73.17	26.83	384.1	2.0

Appendix A: Pilot scale experimental runs
Table A-3a: Biogas composition in R4

Run time (Days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Specific cumulative biogas production (L/kg TVS)	Daily methane production (L/VS)
			% CH ₄	% CO ₂		
1	76.3	76.3	0	100	4.6	4.63
2	29.3	105.6	0	100	6.4	1.77
3	49.8	155.4	0	100	9.4	3.02
4	44.0	199.4	0	100	12.1	2.67
5	34.1	233.5	0	100	14.2	2.07
6	44.7	278.2	0	100	16.9	2.71
7	75.2	353.4	0	100	21.4	4.56
8	37.9	391.2	0	100	23.7	2.30
9	73.1	464.3	0	100	28.2	4.43
10	126.6	590.9	0	100	35.8	7.68
11	105.0	695.9	0	100	42.2	6.37
12	107.4	803.3	0	100	48.7	6.51
13	98.0	901.3	0	100	54.7	5.94
14	87.6	988.8	0	100	60.0	5.31
15	144.2	1133.0	4.4	95.6	68.7	8.75
16	120.4	1253.4	4.0	96.0	76.0	7.30
17	116.0	1369.4	6.1	93.9	83.1	7.04
18	44.2	1413.7	10.1	89.9	85.8	2.68
19	44.5	1458.1	11.4	88.6	88.4	2.70
20	125.5	1583.6	11.8	88.2	96.1	7.61
21	81.8	1665.4	8.4	91.6	101.0	4.96
22	79.4	1744.8	12.2	87.8	105.8	4.82
23	78.5	1823.2	13.3	86.7	110.6	4.76
24	96.2	1919.4	13.7	86.3	116.4	5.83
25	74.8	1994.2	24.4	75.6	121.0	4.53
26	67.9	2062.1	34.1	65.9	125.1	4.12
27	56.0	2118.1	46.0	54.0	128.5	3.40
28	53.2	2171.3	56.2	43.8	131.7	3.23
29	65.8	2237.1	55	45.0	135.7	3.99
30	124.4	2361.5	55	45	143.2	7.55
31	115.9	2477.4	55	45	150.3	7.03
32	163.9	2641.2	55	45	160.2	9.94
33	163.9	2805.1	55	45	170.2	9.94
34	198.4	3003.5	55	45	182.2	12.03
35	177.9	3181.4	55	45	193.0	10.79
36	166.7	3348.1	55	45	203.1	10.11
37	183.6	3531.7	55	45	214.2	11.14
38	183.6	3715.4	55	45	225.4	11.14
39	197.8	3913.2	55	45	237.4	12.00
40	197.8	4111.0	55	45	249.4	12.00
41	108.8	4219.8	55	45	256.0	6.60
42	140.0	4359.8	55	45	264.5	8.49
43	156.7	4516.5	55	45	274.0	9.50
44	143.2	4659.7	55	45	282.7	8.69
45	196.0	4855.7	55	45	294.5	11.89

Appendix B

Appendix B-Table 1a: Leachate characteristics in R1

Run time	pH	Alkalinity mg/L as CaCO ₃	TCOD (mg/L)	NH ₄ -N (mg/L)	TKN (mg/L)	DOC (mg/L)
1	4.2	6000	58000	1400	2520	23300
2	5.5	6000	57000	1540	2940	23300
3	5.07	7500	53200	1680	2240	24260
4	5.13	7000	55000	1400	2940	17900
5	5.38	9000	46000	1260	1820	14940
6	5.87	11000	35000	1400	1820	14220
10	5.89	25000	40000	2100	1820	13900
14	5.73	23000	104000	2240	3640	13540
15	5.72	17000	96000	2380	3920	13570
16	5.73	17000	46000	1540	3640	13960
17	5.74	29000	102000	2660	3710	13860
19	5.73	24000	84000	2660	3920	14120
21	5.78	25000	100000	2660	3220	14530
22	5.8	26000	122000	2660	3220	14520
23	5.85	29000	80000	3080	3360	14600
24	5.87	31000	74000	3080	3360	13670
26	5.9	35000	102000	3080	3920	12980
30	5.87	40000	98000	3220	3360	12980
31	5.95	25000	98000	2940	3360	11960
32	6.01	32000	98000	3080	4130	12890
34	5.96	37000	94000	2940	3920	12560
36	5.93	36000	102000	3500	4200	11700
41	5.92	31000	98000	3640	4200	13060
45	6.02	31000	84000	3500	4130	9095
50	6.23	28000	102000	3710	4130	11701
54	6.67	28000	120000	3780	4410	10597
58	6.95	37000	114000	3780	4620	8546
62	7.16	38000	114000	3850	4410	9546
66	7.25	35000	114000	3780	4970	11320
76	7.5	40000	112000	3850	4970	9000
86	7.35	43500	113000	3920	5040	8500
96	7.85	47000	115000	4060	5040	9000

Appendix B- Table 1b: Leachate characteristics in R2

Run time	pH	Alkalinity mg/L as CaCO₃	TCOD (mg/L)	NH₄-N (mg/L)	TKN (mg/L)	DOC (mg/L)
1	4.21	5000	60000	1680	2520	23300
2	5.11	6000	59000	1820	2940	23300
3	5.09	7000	59000	1400	2240	24260
4	5.28	7000	41000	1680	2940	17900
5	5.61	11000	38000	1400	1820	14940
6	5.68	12000	29000	980	1820	14220
7	5.79	27000	42000	1960	2940	11340
10	6.1	29000	40000	2240	3220	13900
11	6.39	12000	40000	1960	3220	13160
14	6.75	36000	108000	2800	3640	13540
15	6.84	36000	104000	2660	3920	13570
16	6.83	36000	108000	2660	3640	13960
17	7.01	38000	108000	2660	3710	13860
19	7.02	37000	114000	2800	3920	14420
20	6.87	38000	112000	2800	3920	14230
21	7.08	41000	110000	2940	4060	14530
22	7	37000	110000	2800	4060	14520
23	7.02	41000	112000	2940	4060	14600
24	6.97	43000	110000	2940	4340	13670
26	6.9	39000	84000	3080	4340	12980
28	6.88	44000	88000	3220	4340	12980
30	6.92	39000	92000	3220	4620	12980
32	7.12	42000	86000	3220	4340	12890
34	7.15	38000	88000	3220	4130	12560
36	7.19	39000	86000	3640	4480	11700
41	7.36	45000	114000	4060	4620	13060
45	7.51	36000	132000	3640	4480	9095
50	7.62	40000	110000	3780	4620	6701
54	7.66	38000	84000	3780	4620	5997
58	7.66	40000	62000	4060	5040	5746
62	7.69	40000	60000	4130	4970	5460
66	7.63	37000	58000	4200	5320	11320
69	7.18	44000	48000	3920	5320	10000
76	7.7	44000	38000	3920	5740	10000
83	7.81	44000	18000	4550	5810	8500
96	7.86	48000	18000	4480	6160	4000

Appendix B- Table 1c: Leachate characteristics in R4

Run time	pH	Alkalinity mg/L as CaCO₃	TCOD (mg/L)	NH₄-N (mg/L)	TKN (mg/L)	DOC (mg/L)
1	4.71	6000	42000	1120	1540	7000
2	4.4	7000	50000	1120	1545	7000
6	4.01	6000	60000	1680	2800	17000
12	5	21000	124000	1680	3080	21100
18	6.19	30000	140000	1820	4200	25700
22	6.33	30000	120000	1820	4200	23400
26	7.1	28000	102000	1680	4620	22300
31	7.2	31000	100000	3220	5040	21300
34	7.4	32000	100000	3220	5600	21200
40	7.61	35000	99000	3710	5670	20000
45	7.7	40000	100000	3640	5740	17000

Appendix C
Lap-scale experimental data

Appendix C-1- OF-MSW reactor data

Run time (days)	chromatographic area of CH ₄		Mass of CH ₄ (μg) in 0.2 ml		Mass of CH ₄ per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	cumulative volume production (mL)	Correct Cumulative volume production (L/kg VS)
	Before removal	After removal	Before removal	After removal	Before removal	After removal					
1	47081	37640	8.36	6.68	0.10	0.08	0.02	0.02	0.12	177.8	15.81
2	250544	146423	44.49	26.00	0.52	0.30	0.21	0.23	0.75	1145.3	101.84
4	250544	246423	44.49	43.76	0.52	0.51	0.01	0.24	0.76	1158.2	102.92
6	314466	219539	55.85	38.99	0.65	0.45	0.20	0.44	1.08	1657.9	147.31
8	354472	335771	62.95	59.63	0.73	0.69	0.04	0.48	1.21	1842.5	163.72
10	311151	279792	55.26	49.69	0.64	0.58	0.06	0.54	1.18	1804.9	160.36
13	361591	288319	64.21	51.20	0.74	0.59	0.15	0.69	1.44	2194.0	194.95
15	331447	293093	58.86	52.05	0.68	0.60	0.08	0.77	1.45	2219.8	197.24
17	366643	291496	65.11	51.77	0.75	0.60	0.15	0.93	1.68	2566.9	228.11
20	378368	291821	67.19	51.82	0.78	0.60	0.18	1.10	1.88	2876.0	255.57
24	352789	283558	62.65	50.36	0.73	0.58	0.14	1.25	1.97	3013.3	267.77
27	316510	274445	56.21	48.74	0.65	0.56	0.09	1.33	1.98	3031.5	269.39
29	273209	228285	48.52	40.54	0.56	0.47	0.09	1.42	1.99	3036.6	269.74
37	252322	204879	44.81	36.38	0.52	0.42	0.10	1.52	2.04	3120.2	277.13
41	299434	297678	53.18	52.86	0.62	0.61	0.00	1.53	2.14	3273.9	290.71
45	300107	295971	53.30	52.56	0.62	0.61	0.01	1.53	2.15	3289.0	291.95
54	327999	304891	58.25	54.15	0.68	0.63	0.05	1.58	2.26	3449.4	306.27
57	328128	294606	58.27	52.32	0.68	0.61	0.07	1.65	2.33	3555.3	315.62
60	312211	296459	55.45	52.65	0.64	0.61	0.03	1.68	2.33	3554.7	315.55
67	320962	296343	57.00	52.63	0.66	0.61	0.05	1.73	2.39	3659.7	324.85
70	298119	262399	52.94	46.60	0.61	0.54	0.07	1.81	2.42	3700.2	328.44
81	338958	329886	60.20	58.58	0.70	0.68	0.02	1.83	2.52	3857.2	342.36
87	355736	362946	63.18	64.46	0.73	0.75	0.01	1.81	2.54	3887.3	345.03
97	352820	335433	62.66	59.57	0.73	0.69	0.04	1.85	2.57	3932.8	349.08
100	349015	342015	61.98	60.74	0.72	0.70	0.01	1.86	2.58	3942.9	349.97

Appendix C-2- OF-MSW reactor data

Run time (days)	chromatographic area of CH ₄		Mass of CH ₄ (μg) in 0.2 ml		Mass of CH ₄ per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	cumulative volume production (mL)	Corrected (mL)	Correct cumulative volume production (L/kg VS)
	Before removal	After removal	Before removal	After removal	Before removal	After removal						
1	73097	49756	12.98	8.84	0.15	0.10	0.05	0.05	0.20	303.34	298.25	26.98
2	143160	95288	25.42	16.92	0.29	0.20	0.10	0.15	0.44	674.29	623.24	59.94
4	286258	179123	50.84	31.81	0.59	0.37	0.22	0.37	0.96	1461.37	1356.89	129.92
6	422624	241842	75.05	42.95	0.87	0.50	0.37	0.74	1.61	2458.93	2298.78	218.62
8	492993	293262	87.55	52.08	1.01	0.60	0.41	1.15	2.16	3308.51	3134.22	294.20
10	51271	44902	9.11	7.97	0.11	0.09	0.01	1.16	1.27	1939.15	1710.78	172.31
13	362824	350893	64.43	62.32	0.75	0.72	0.02	1.19	1.93	2956.64	2743.65	262.85
15	315721	296899	56.07	52.73	0.65	0.61	0.04	1.23	1.88	2867.68	2643.78	254.93
17	305099	269800	54.18	47.91	0.63	0.56	0.07	1.30	1.93	2945.30	2719.51	261.83
20	304424	292269	54.06	51.90	0.63	0.60	0.03	1.32	1.95	2981.41	2755.36	265.05
24	308794	286823	54.84	50.94	0.64	0.59	0.05	1.37	2.01	3064.26	2796.89	272.38
27	258577	223689	45.92	39.72	0.53	0.46	0.07	1.44	1.97	3016.05	2857.85	268.19
29	225759	212238	40.09	37.69	0.46	0.44	0.03	1.47	1.93	2955.35	2783.02	262.78
37	237813	164198	42.23	29.16	0.49	0.34	0.15	1.62	2.11	3224.81	3111.34	286.81
41	310444	304637	55.13	54.10	0.64	0.63	0.01	1.63	2.27	3471.53	3114.11	308.52
45	305681	294101	54.29	52.23	0.63	0.61	0.02	1.66	2.29	3492.97	3178.29	310.47
54	305945	293620	54.33	52.14	0.63	0.60	0.03	1.68	2.31	3532.57	3202.83	313.98
57	308950	284216	54.87	50.47	0.64	0.58	0.05	1.73	2.37	3619.82	3286.20	321.74
60	306117	278441	54.36	49.45	0.63	0.57	0.06	1.79	2.42	3697.96	3366.31	328.70
67	322240	298015	57.23	52.92	0.66	0.61	0.05	1.84	2.50	3824.87	3499.43	339.99
70	274451	265482	48.74	47.15	0.56	0.55	0.02	1.86	2.42	3702.77	3385.71	329.14
81	354097	333441	62.88	59.22	0.73	0.69	0.04	1.90	2.63	4018.26	3619.64	357.13
87	403610	327515	71.68	58.16	0.83	0.67	0.16	2.06	2.89	4413.35	3964.38	392.23
97	361709	363173	64.24	64.50	0.74	0.75	0.00	2.05	2.80	4276.95	3870.87	380.14
100	379224	347130	67.35	61.65	0.78	0.71	0.07	2.12	2.90	4432.99	4132.50	394.13

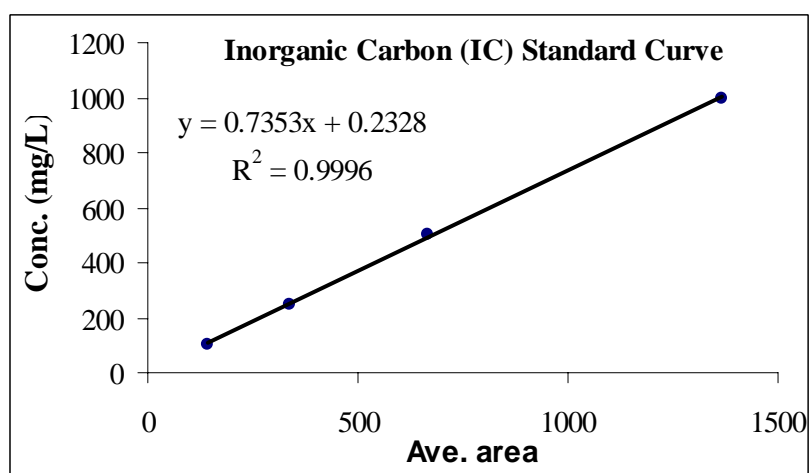
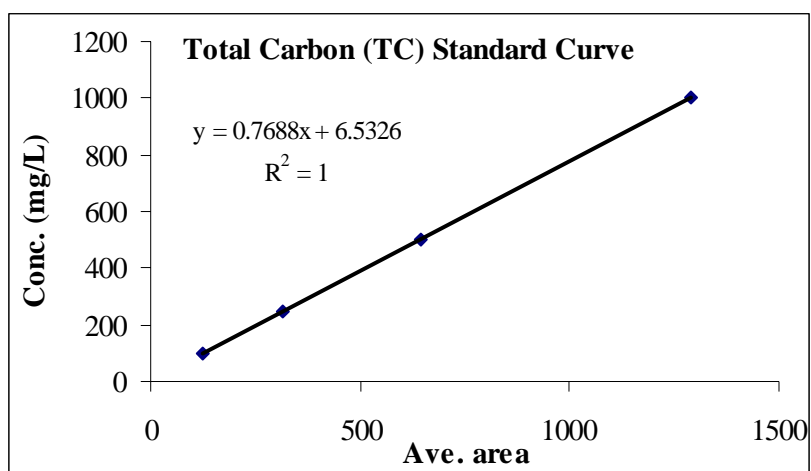
Appendix C-4- Blank reactor data

Run time (days)	chromatographic area of CH ₄		Mass of CH ₄ (μg) in 0.2 ml		Mass of CH ₄ per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	cumulative volume production (mL)	cumulative volume production (L)
	Before removal	After removal	Before removal	After removal	Before removal	After removal					
1	10420	10400	0.19	1.85	0.00	0	0.00	0.002	0.00	6.56	0.01
2	15529	13441	2.76	2.39	0.03	0.03	0.00	0.006	0.04	58.69	0.06
4	36359	32075	6.46	5.70	0.07	0.07	0.01	0.015	0.09	137.68	0.14
6	48734	42884	8.65	7.62	0.10	0.09	0.01	0.027	0.13	195.01	0.20
8	54095	52264	9.61	9.28	0.11	0.11	0.00	0.031	0.14	217.63	0.22
10	55654	52708	9.88	9.36	0.11	0.11	0.01	0.037	0.15	231.80	0.23
13	63339	60331	11.25	10.71	0.13	0.12	0.01	0.043	0.17	265.43	0.27
15	65744	65700	11.68	11.67	0.14	0.14	0.00	0.043	0.18	273.14	0.27
17	66011	62497	11.72	11.10	0.14	0.13	0.01	0.051	0.19	285.03	0.29
20	72075	65692	12.80	11.67	0.15	0.14	0.01	0.064	0.21	324.18	0.32
24	71963	66880	12.78	11.88	0.15	0.14	0.01	0.074	0.22	339.82	0.34
27	70925	69513	12.60	12.34	0.15	0.14	0.00	0.077	0.22	340.99	0.34
29	80177	56383	14.24	10.01	0.17	0.12	0.05	0.126	0.29	444.94	0.44
37	75579	56698	13.42	10.07	0.16	0.12	0.04	0.165	0.32	489.86	0.49
41	108517	110796	19.27	19.68	0.22	0.23	0.00	0.160	0.38	586.30	0.59
45	129023	116074	22.91	20.61	0.27	0.24	0.03	0.187	0.45	691.53	0.69
54	120293	127797	21.36	22.70	0.25	0.26	0.02	0.172	0.42	640.46	0.64
57	133012	125180	23.62	22.23	0.27	0.26	0.02	0.188	0.46	705.11	0.71
60	138158	133057	24.54	23.63	0.28	0.27	0.01	0.198	0.48	737.34	0.74
67	139901	128893	24.85	22.89	0.29	0.27	0.02	0.221	0.51	777.44	0.78
70	133122	123210	23.64	21.88	0.27	0.25	0.02	0.241	0.52	787.30	0.79
81	151378	153546	26.88	27.27	0.31	0.32	0.00	0.237	0.55	837.90	0.84
87	152305	152100	27.05	27.01	0.31	0.31	0.00	0.237	0.55	841.46	0.84
97	154399	156410	27.42	27.78	0.32	0.32	0.00	0.233	0.55	841.72	0.84
100	176160	196137	31.28	34.83	0.36	0.40	0.04	0.192	0.55	847.33	0.85

Appendix C-6- Blank reactor data

Run time (days)	chromatographic area of CH ₄		Mass of CH ₄ (μg) in 0.2 ml		Mass of CH ₄ per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	cumulative volume production (mL)	cumulative volume production (L)
	Before removal	After removal	Before removal	After removal	Before removal	After removal					
1	8082	6791	0.14	1.21	0.00	0.00	0.00	0.00	0.00	5.08	0.01
2	14727	14033	2.62	2.49	0.03	0.03	0.00	0.00	0.03	51.05	0.05
4	30173	28629	5.36	5.08	0.06	0.06	0.00	0.01	0.07	104.49	0.10
6	43551	39231	7.73	6.97	0.09	0.08	0.01	0.02	0.10	160.16	0.16
8	46176	44308	8.20	7.87	0.10	0.09	0.00	0.02	0.11	174.29	0.17
10	58878	54388	10.46	9.66	0.12	0.11	0.01	0.03	0.15	228.36	0.23
13	55875	57762	9.92	10.26	0.12	0.12	0.00	0.02	0.14	212.98	0.21
15	57621	55896	10.23	9.93	0.12	0.12	0.00	0.03	0.15	223.90	0.22
17	58374	58525	10.37	10.39	0.12	0.12	0.00	0.03	0.15	225.79	0.23
20	61104	63752	10.85	11.32	0.13	0.13	0.01	0.02	0.15	226.05	0.23
24	72229	70217	12.83	12.47	0.15	0.14	0.00	0.03	0.17	267.37	0.27
27	47854	58188	8.50	10.33	0.10	0.12	0.02	0.01	0.10	158.20	0.16
29	49030	45715	8.71	8.12	0.10	0.09	0.01	0.01	0.11	172.32	0.17
37	21646	12971	3.84	2.30	0.04	0.03	0.02	0.03	0.07	113.48	0.11
41	98444	97685	17.48	17.35	0.20	0.20	0.00	0.03	0.23	357.43	0.36
45	105026	125197	18.65	22.23	0.22	0.26	0.04	0.01	0.21	314.68	0.31
54	107199	104586	19.04	18.57	0.22	0.22	0.01	0.00	0.22	329.74	0.33
57	108129	107823	19.20	19.15	0.22	0.22	0.00	0.00	0.22	333.62	0.33
60	104266	101029	18.52	17.94	0.21	0.21	0.01	0.00	0.22	331.66	0.33
67	101449	100606	18.02	17.87	0.21	0.21	0.00	0.00	0.21	325.45	0.33
70	91365	83947	16.23	14.91	0.19	0.17	0.02	0.02	0.21	317.06	0.32
81	113591	109888	20.17	19.52	0.23	0.23	0.01	0.03	0.26	398.62	0.40
87	124668	119737	22.14	21.26	0.26	0.25	0.01	0.04	0.29	448.97	0.45
97	117197	123362	20.81	21.91	0.24	0.25	0.01	0.02	0.27	406.08	0.41
100	76383	69140	13.56	12.28	0.16	0.14	0.01	0.04	0.20	300.48	0.30

1.DOC standard curve





Sequential Dry Batch Anaerobic Digestion of Organic Fraction of Municipal Solid Waste

Nguyen Quang Huy

Examination Committee: Prof. C. Visvanathan (Chairperson)

Dr. Nguyen Thi Kim Oanh

Dr. Thammarat Koottatep

Outline

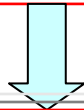
- Introduction
- Background
- Objectives
- Results and Discussions
- Conclusion and Recommendations





Background

**Rapid growth of population with
unplanned urbanization**



- **Cities in Asia generated 0.76 million tons per day of MSW**
- **Rate will jump to about 1.8 million tons per day 2025 (WB 1999)**



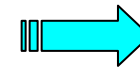
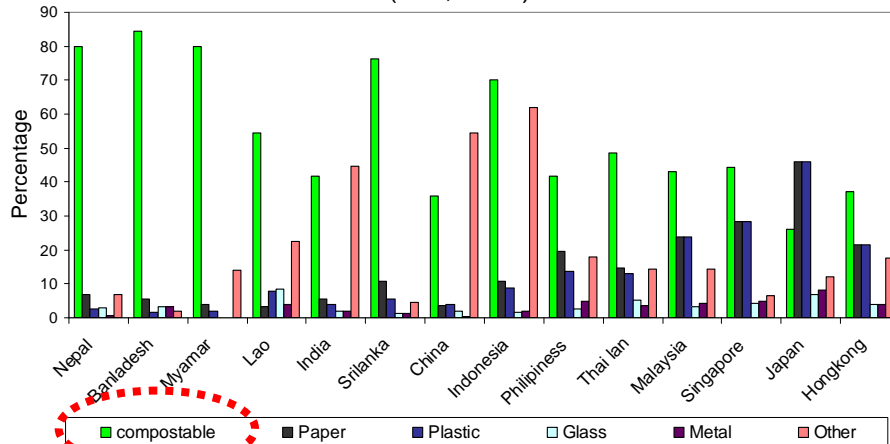
Energy crisis

Water pollution

Global warming

Background (Cont.)

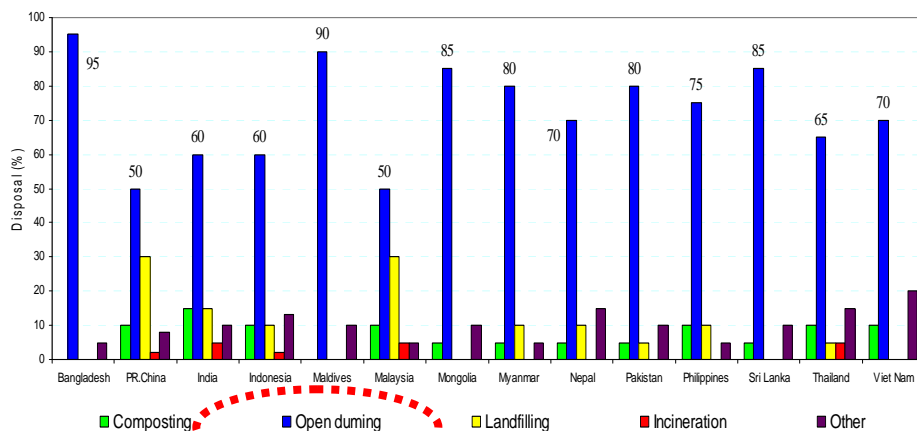
Composition of Urban Solid Waste in Asian Countries
(WB, 1999)



Problems with open dumping

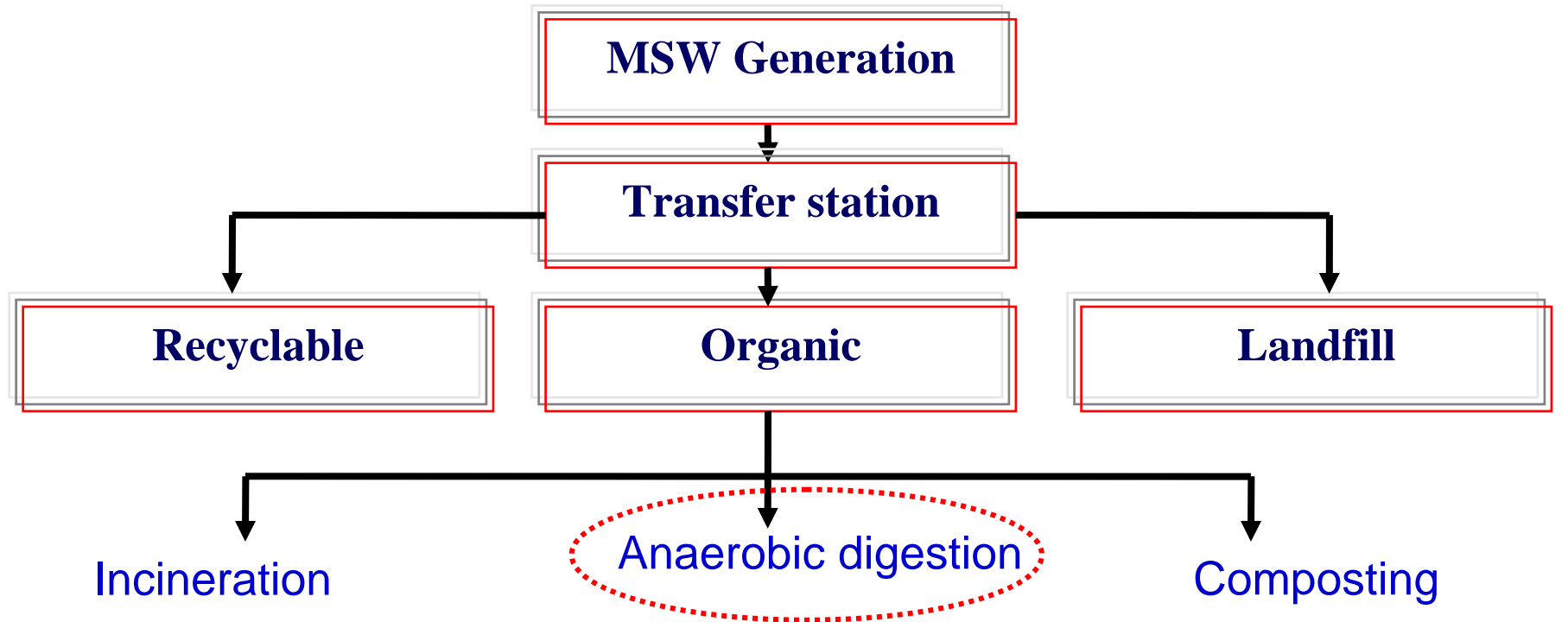
- Odor problem
- Water pollution
- Air pollution
- Human and environmental health effects

Disposal methods of MSW in Asian Countries





Integrate Management Solid Management



Advantage:

- Reduce volume of waste

Disadvantage

- High capital, operating & maintenance cost

Advantage:

- Reduce volume of waste
- Produce energy
- Reduce odor and methane emission to atmosphere

Disadvantage

- Start-up of the process requires long period of time. Edelman (1999)

Advantage:

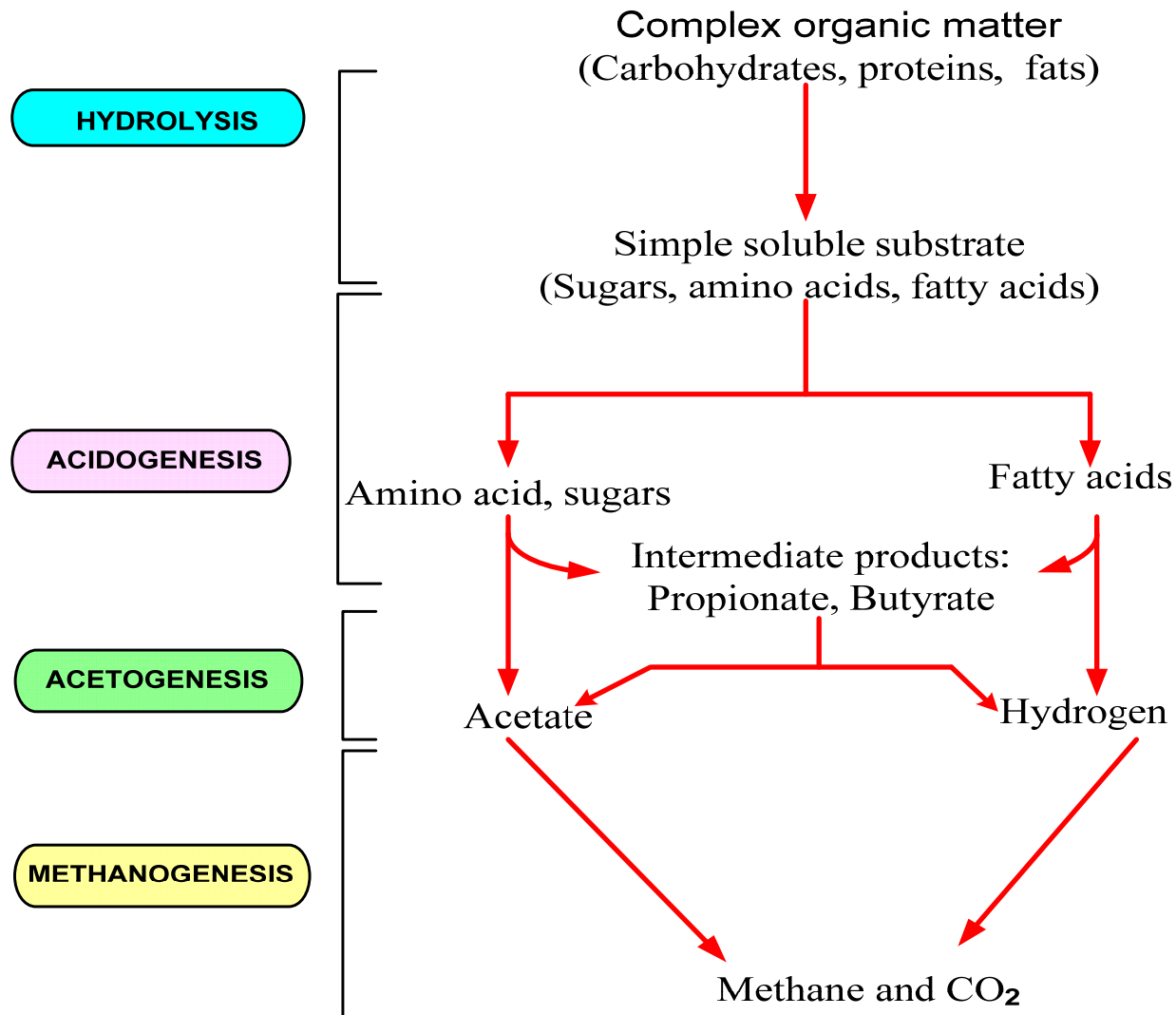
- Reduce volume of waste
- Recover conversion products and energy

Disadvantage

- Odor problem



Concept of Anaerobic Digestion





Objectives and Scope of Study

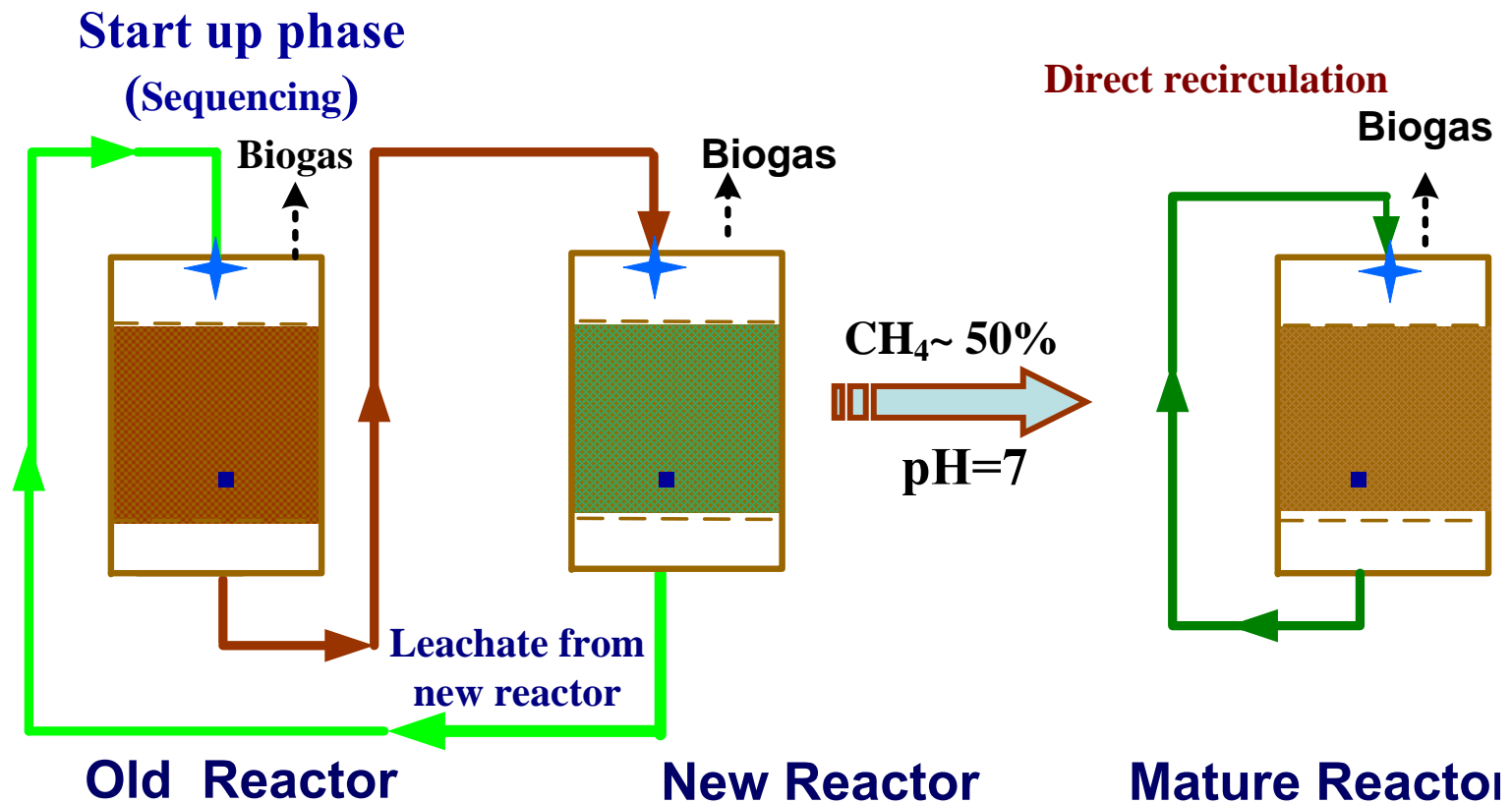
➡ Objectives of the study

- To investigate the performance of Sequential batch anaerobic digestion process on treating the organic fraction of MSW
- To investigate performance of windrow composting system as a post-treatment technology suitable complete stabilization of digested waste

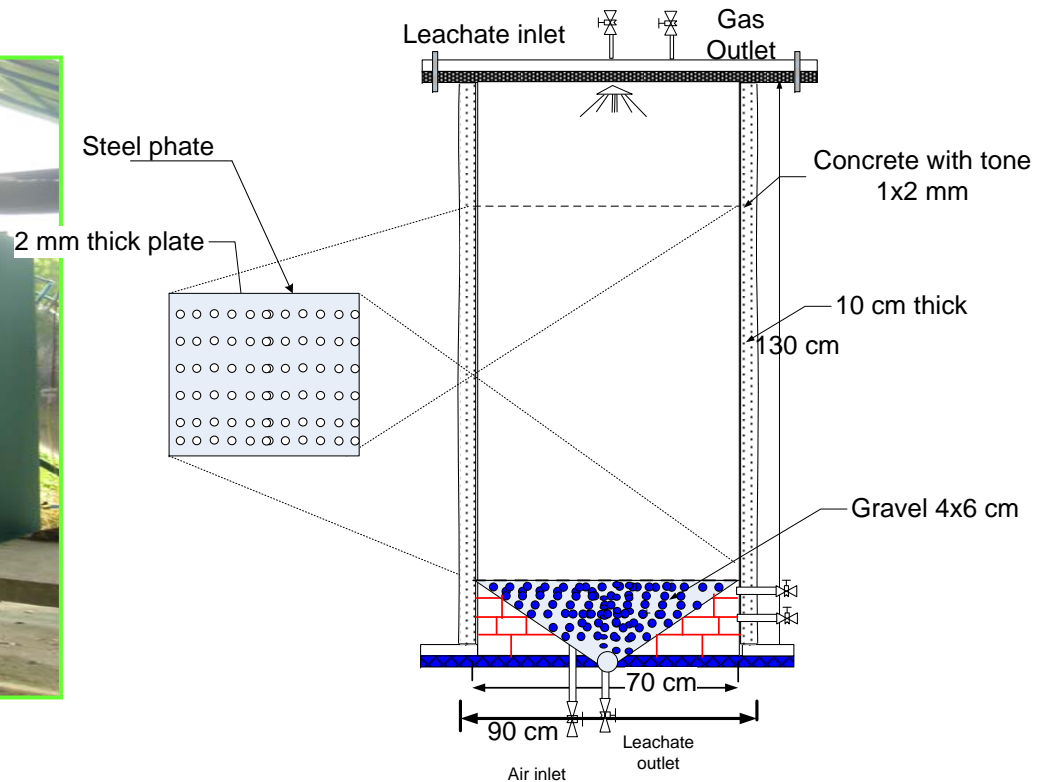
➡ Scope of the study

- MSW was collected from AIT campus
- Biochemical Methane Potential (BMP) test was conducted in laboratory scale
- Sequential batch anaerobic digestion experiment was done in pilot scale experiment

SEBAC Concept



Problem Faced in Concrete Reactors



Leakages in the reactors

Problem Faced in Concrete Reactors (Cont...)



Leakage in
outside reactor

Leakage in bottom
reactor)

After **one month** found leaking
in between concrete and iron



Run

The reactors were link
together (**spend one month**)

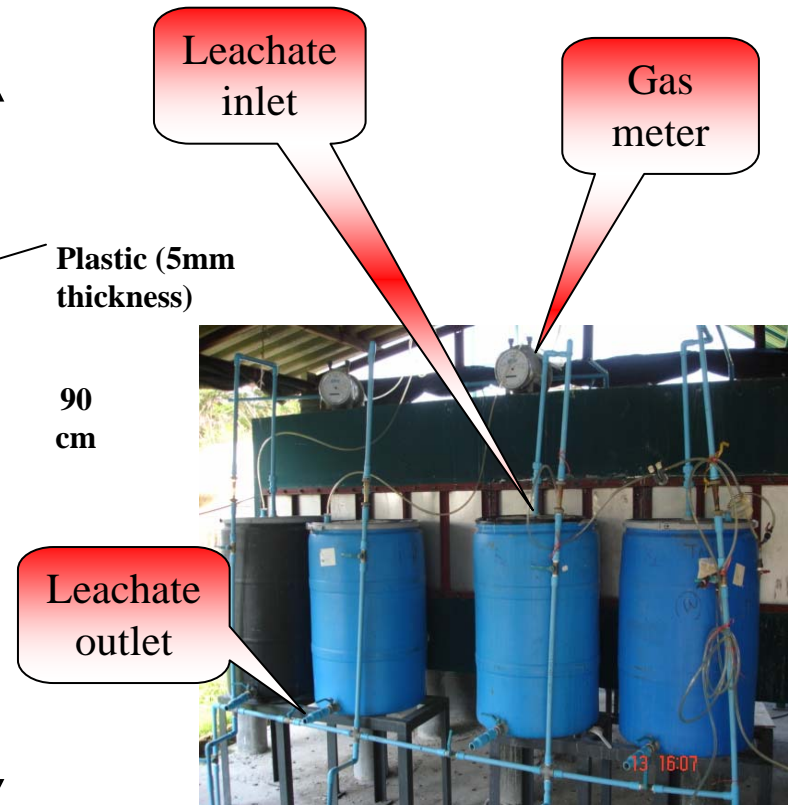
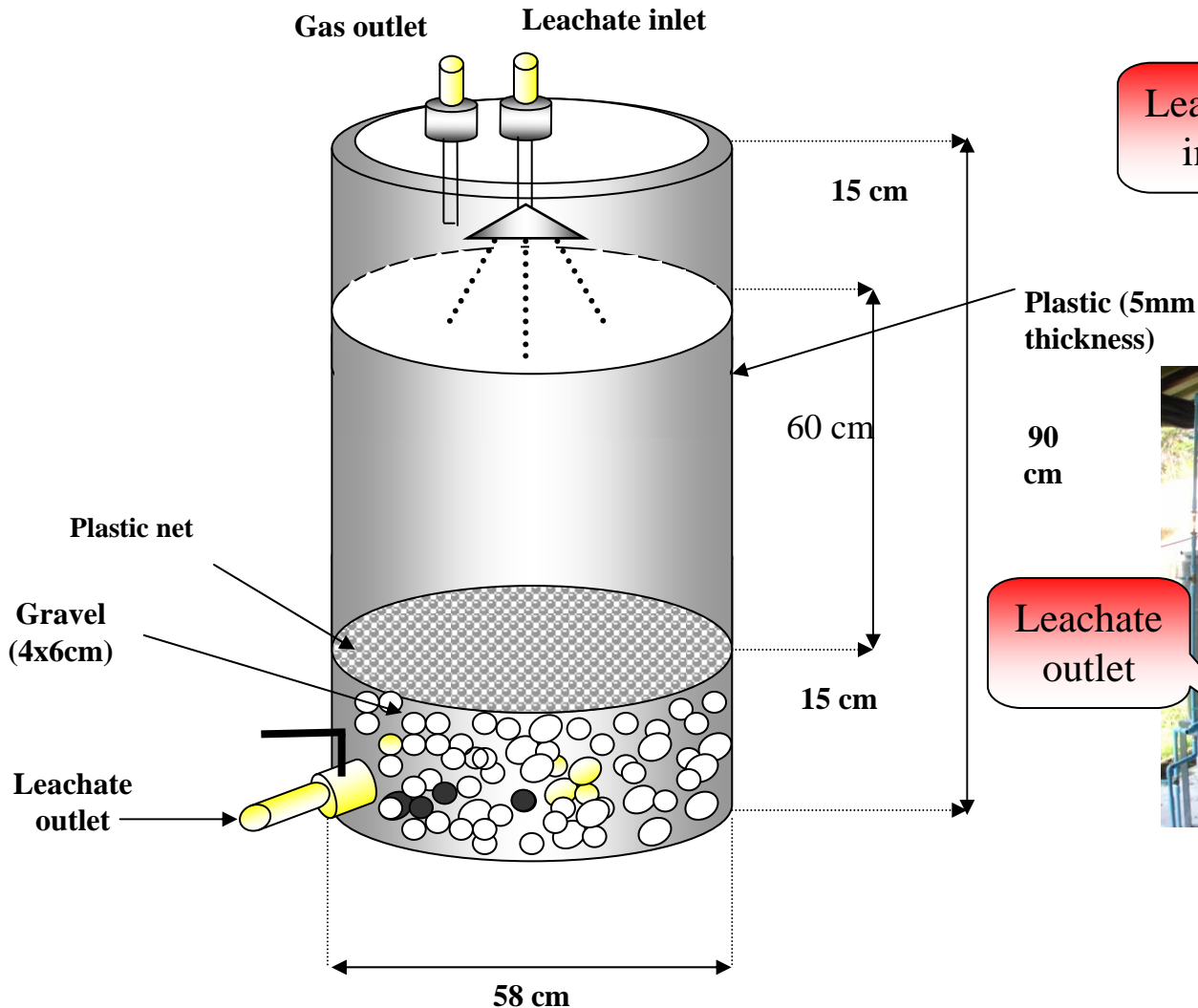
One month

or repair &
check

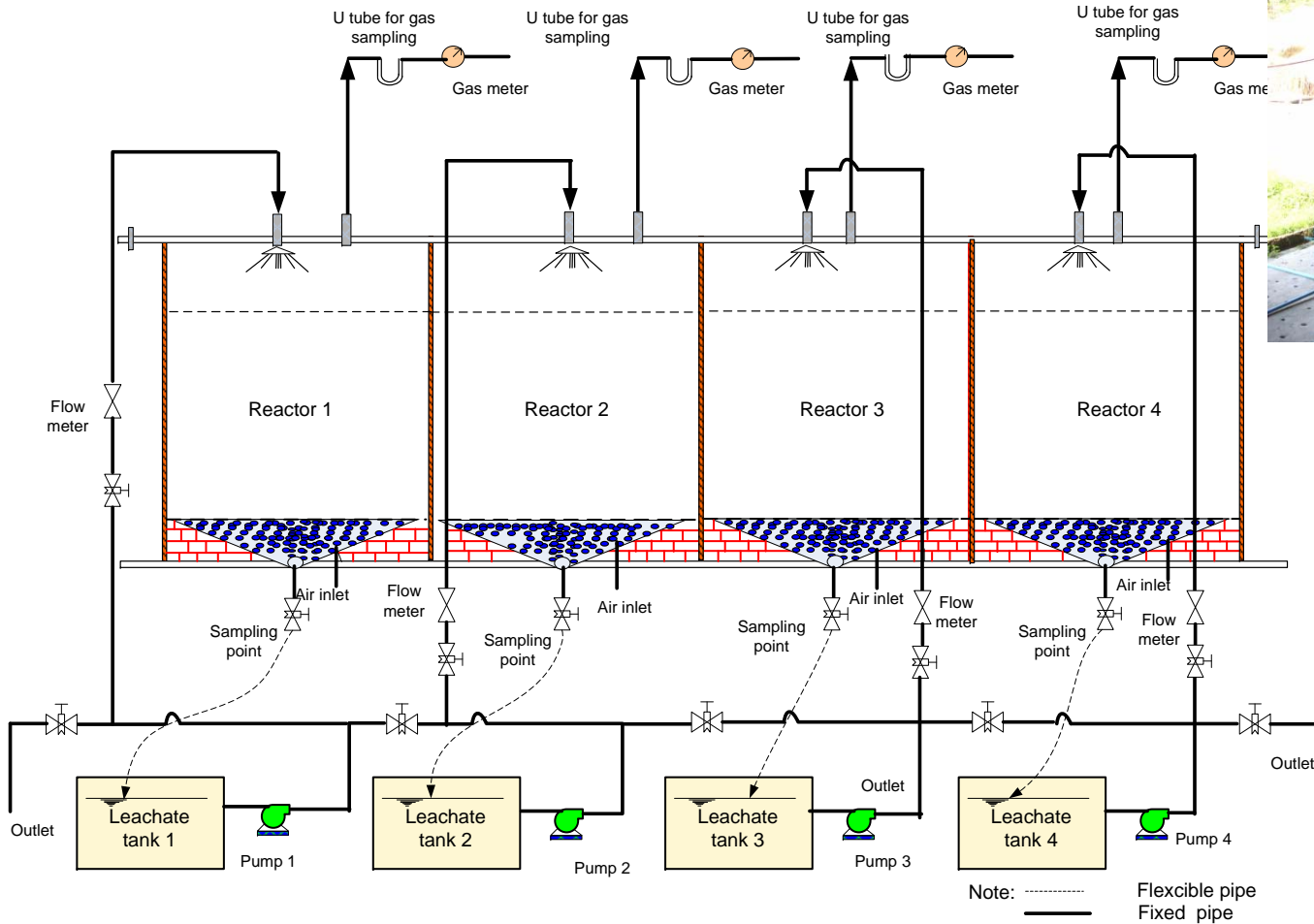




Anaerobic Reactor Design



Pilot Scale Digestion System



Feedstock Preparation

Pulverized



Weighting



Solid weight+inoculum



Loaded in the reactors



Experimental run	Density (Kg/m ³)	Moisture content (%ww)	Total solid waste (%ww)	Total Volatile solid (%ww)
Run 1				
Reactor 1	650	78.7	21.3	84.7
Reactor 2	650	78.2	21.8	85
Reactor 3	(Inoculums reactor)			
Run 2				
Reactor 4	650	79.5	20.5	82.8

Process in Sequential Batch Operation

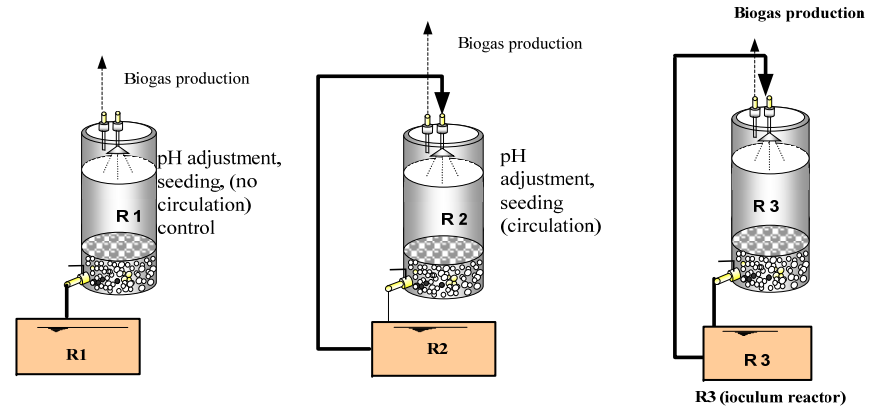
Variables:

- R1 was used as control reactor without circulation
- R2 was operated on circulation of its own leachate
- R3 was only fed with inoculum

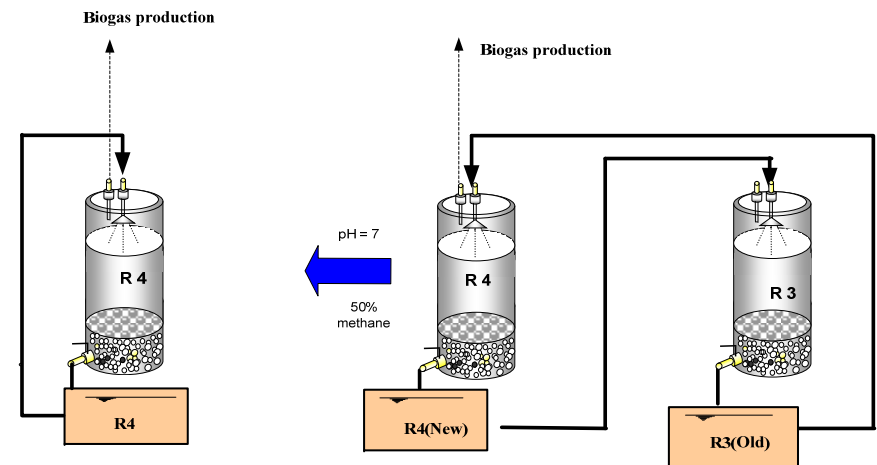
Variables:

- R4 was coupled with R3.
- Leachate was recirculated between the old and the new reactor for start up,
- R4 & R3 were uncoupled when pH in R4 reaches 7 and methane yield = 50%,
- R4 was circulated with its own leachate.

Run 1



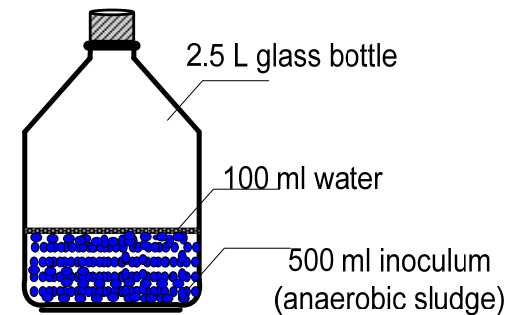
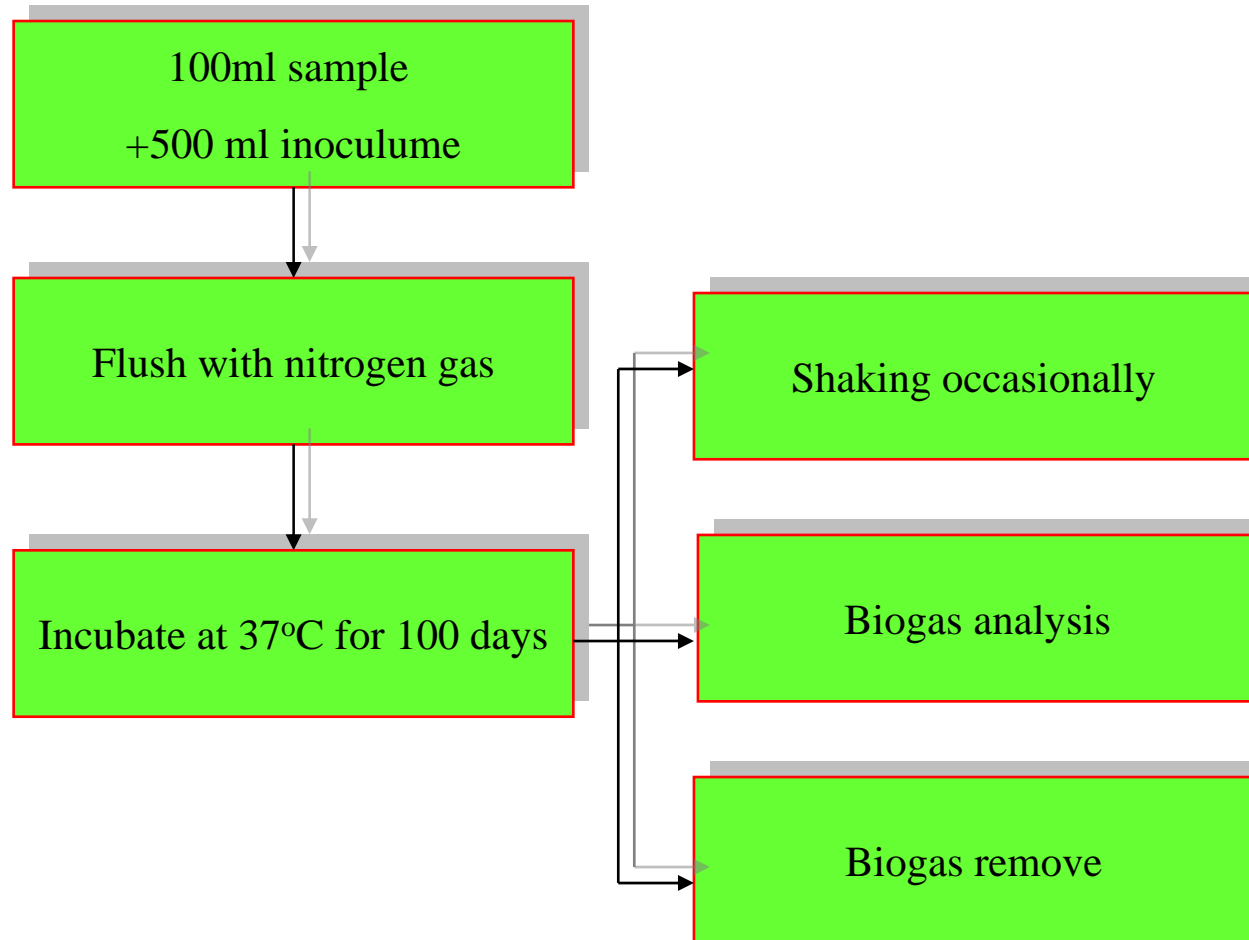
Run 2





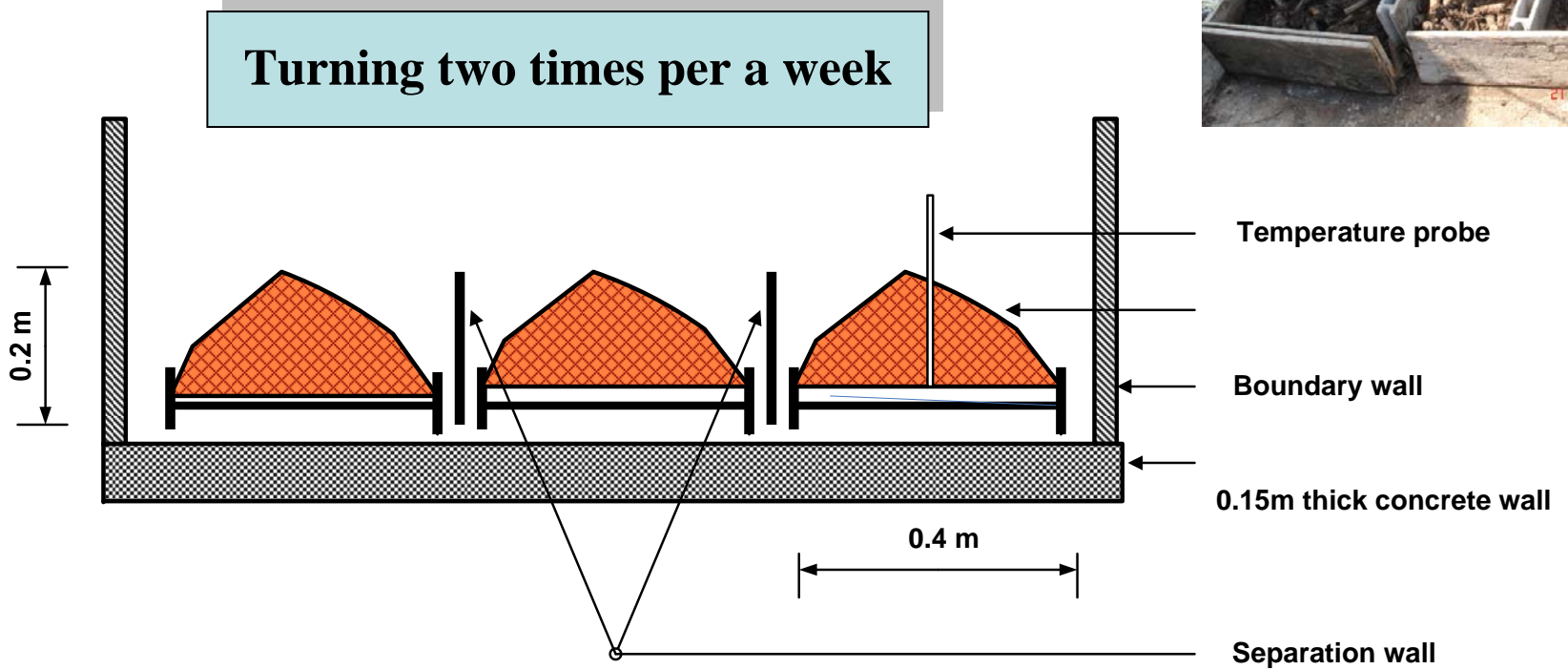
BMP Test Procedure

BMP test (lab-scale) Hansen et al., 2003



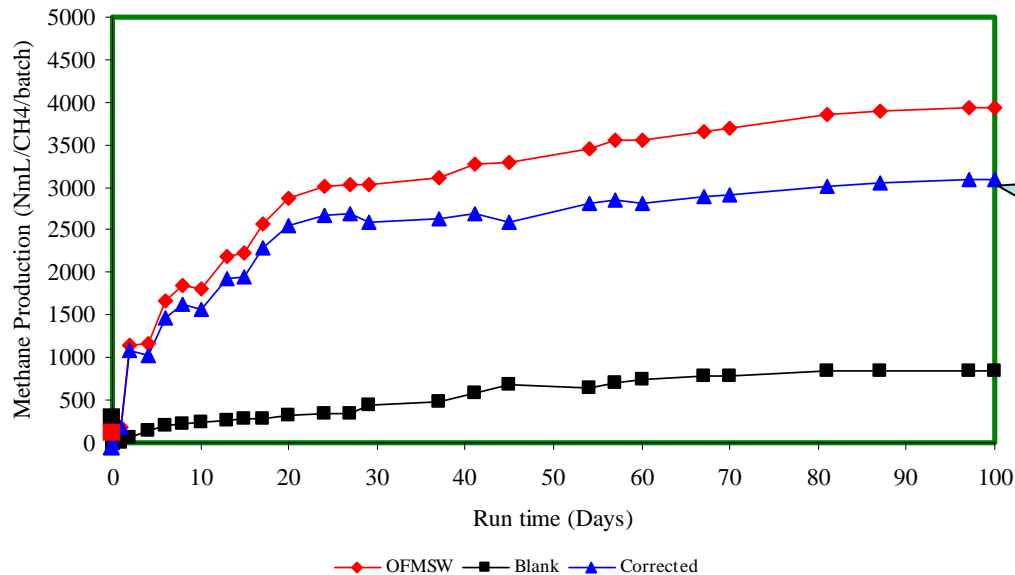


Design of Windrow Composting



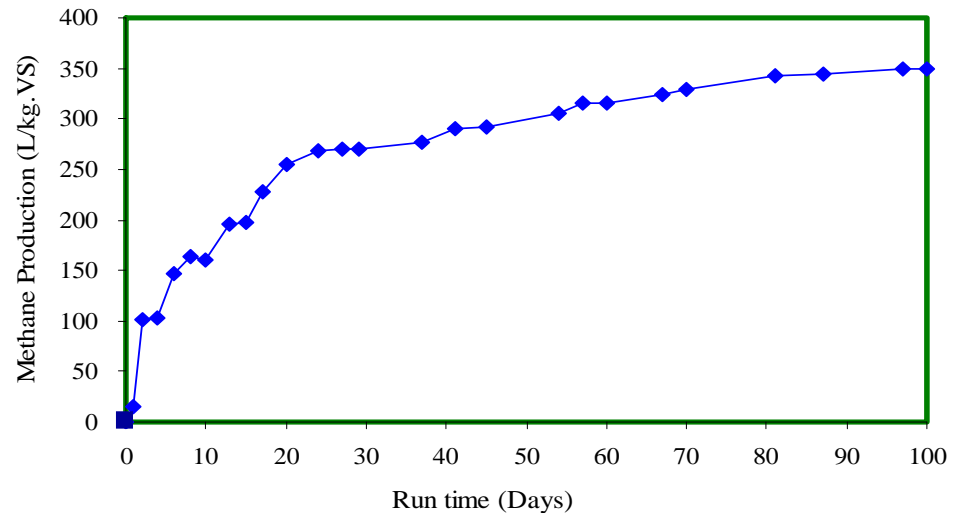


Results and Discussions



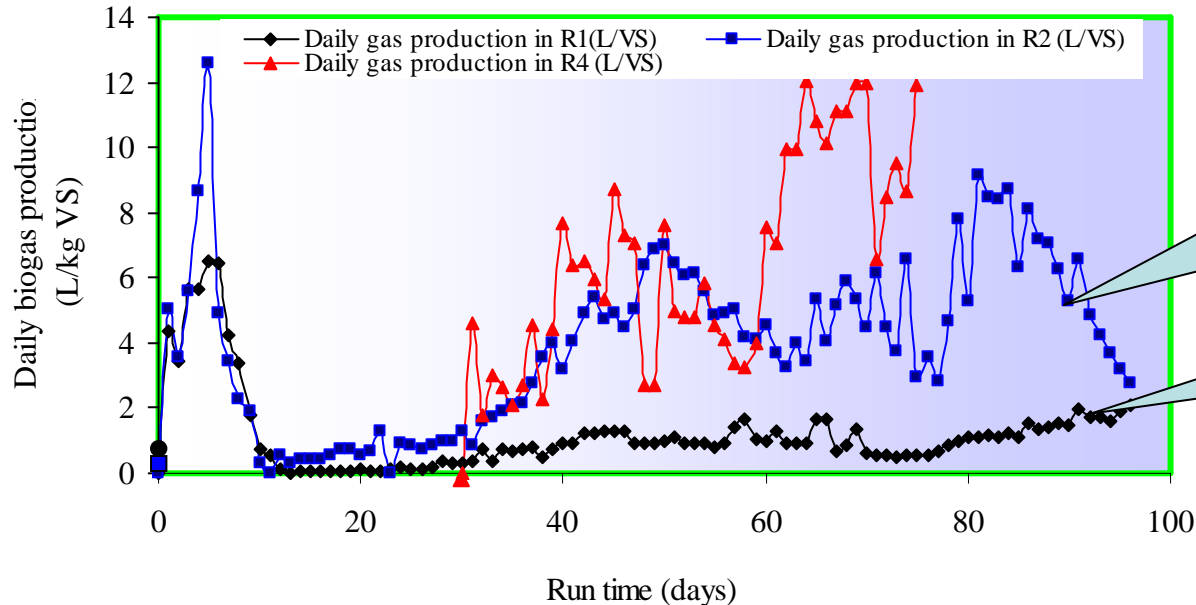
■ After 100 days of mesophilic incubation showed that for each kg VS of the fresh waste, around 349 L methane produced

Cumulative Biogas Production in BMP test (phase 1)



Results and Discussions (cont..)

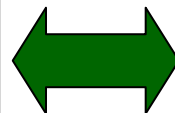
Daily Biogas Production



Total biogas yield was
5428 L in R2

Total biogas yield was
1628 L in R1

Average methane
production rate of R2 was 3
L/kg VS/d

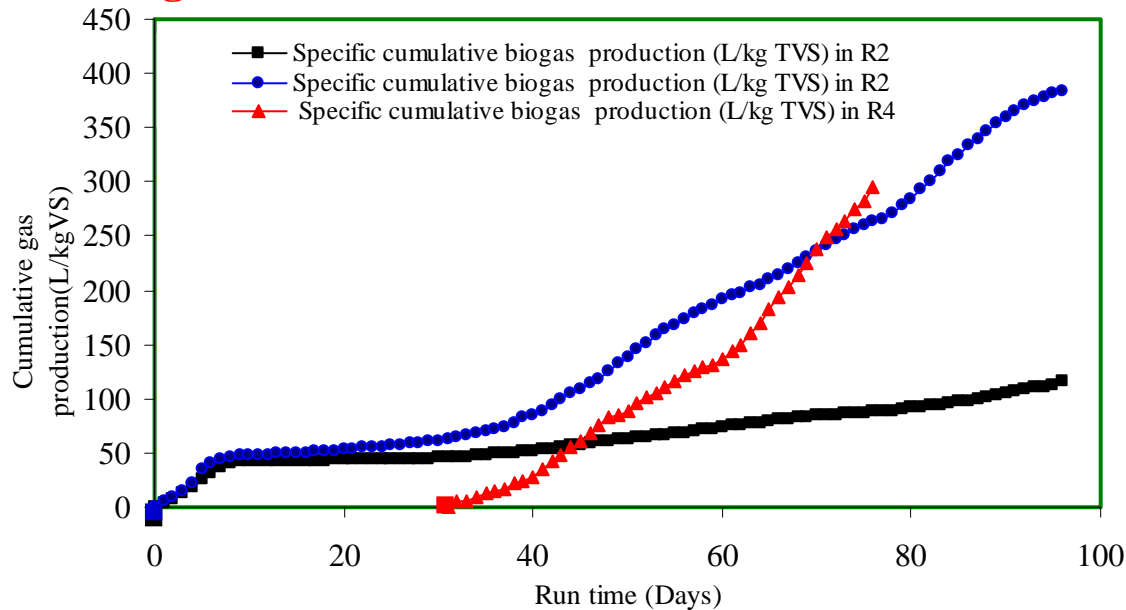


Average methane
production rate of R2 was 5
L/kg VS/d



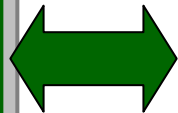
Results and Discussions (cont..)

Cumulative Biogas Production



R1

115 L/kg VS



R2

384 L/kg VS



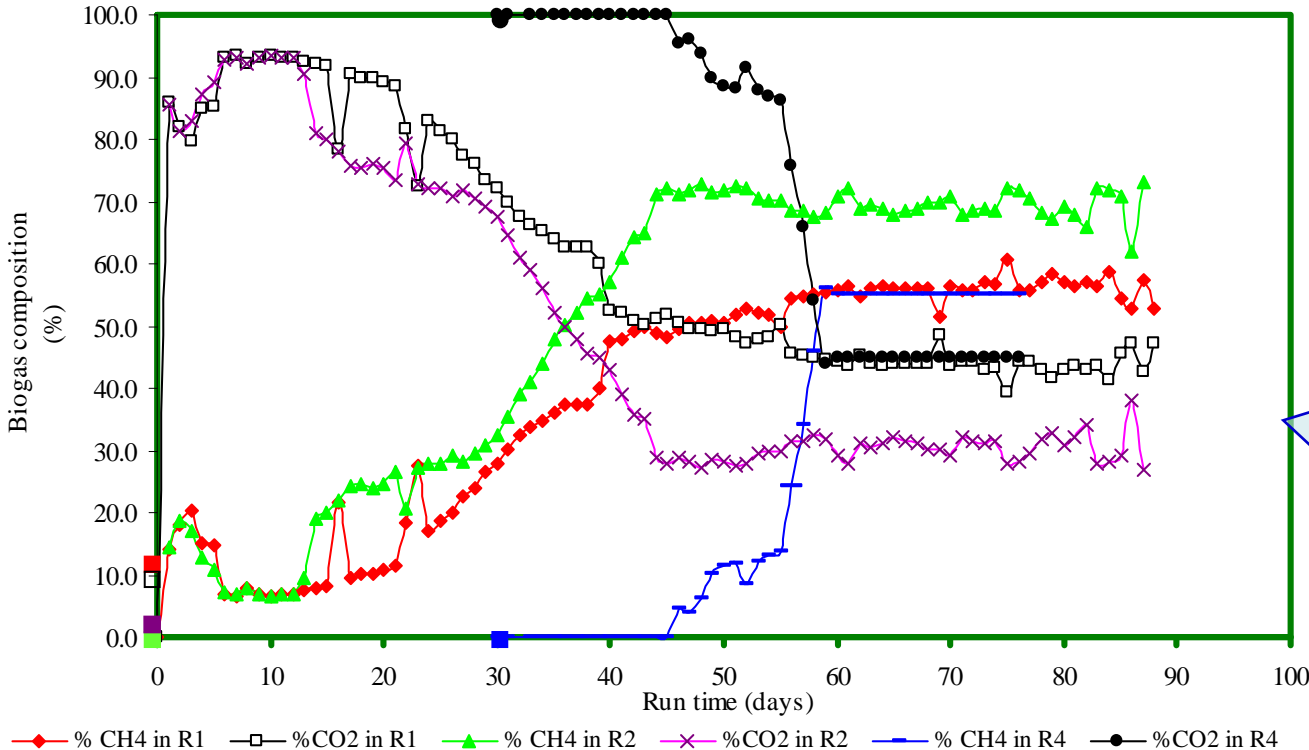
R4

249 L/kg VS

Results and Discussions (cont..)

Biogas composition

Farquhar and Rovers, 1973 reported that methanogenesis was marked by a methane production of approximately 50–60% and by a production of carbon dioxide approximately 40–50%



R1

Methane composition
reached to 50% on day 41

R2

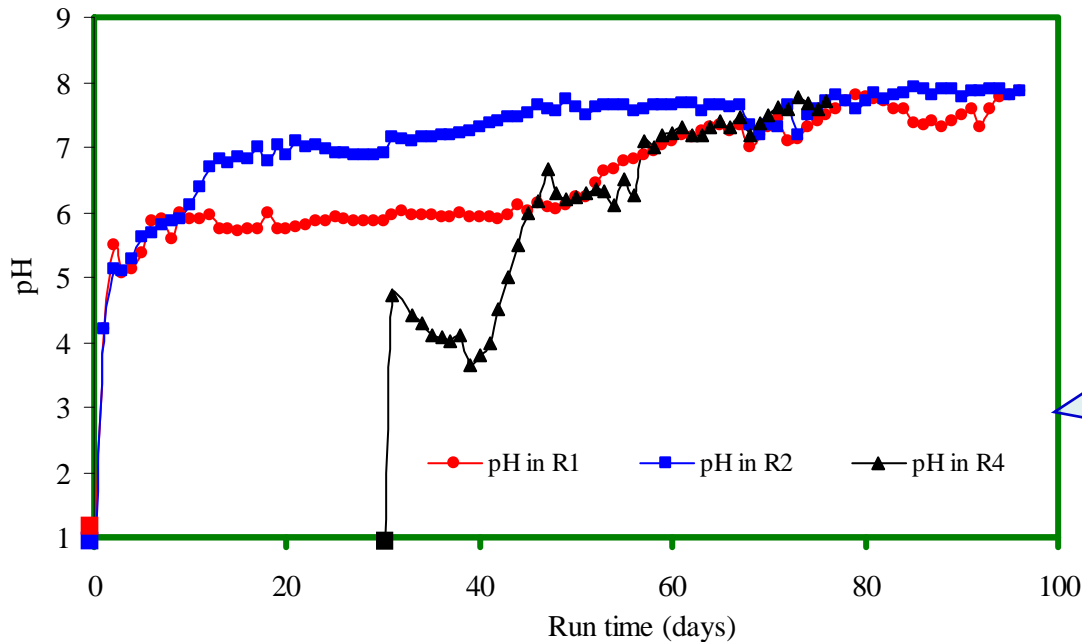
Methane composition
reached to 50% on day 36

R4

Methane composition
reached to 50% on day 28

Results and Discussions (cont..)

pH



Vavilin (2006) showed that inhibition is related either directly or indirectly to low pH.

Kruempelbeck (1999) and Inancet (1996), methanogenesis was favored at a pH 6.4–7.2

R1

pH reached to 7 on day 58

R2

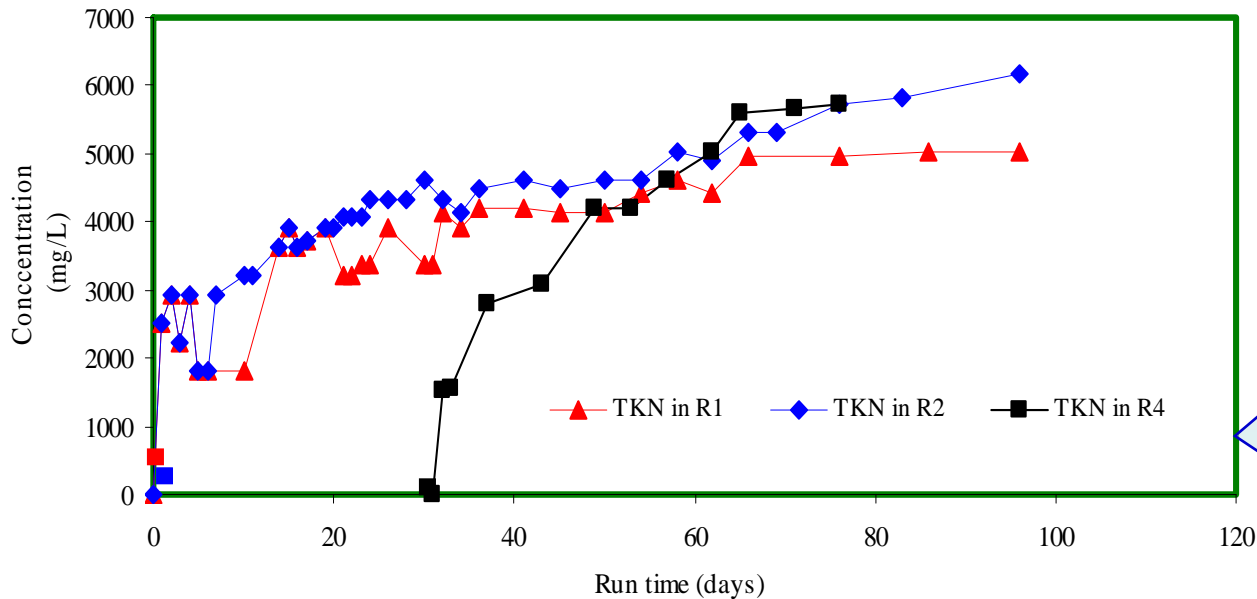
pH reached to 7 on day 17

R4

pH reached to 7 on day 26

Results and Discussions (cont..)

TKN concentration



Illustrated daily concentration of TKN is total soluble nitrogen and ammonia nitrogen which could reflex the daily hydrolysis of protein in anaerobic digestion.

R1

Total N reached to 5 g/L
on day 81

R2

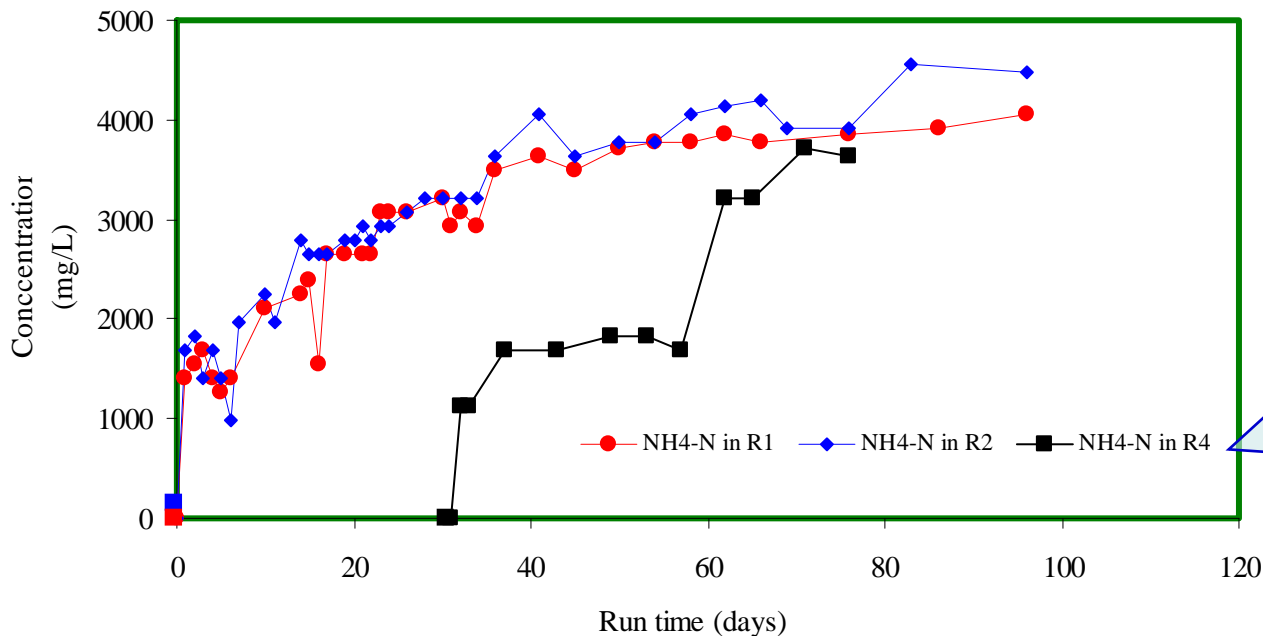
Total N reached to 5 g/L
on day 58

R4

Total N reached to 5 g/L
on day 26

Results and Discussions (cont..)

Ammonia-nitrogen concentration



- A result of decomposition of organic matter containing nitrogen such as protein and amino acids
- Quite important for possible inhibition of methane production under anaerobic conditions

R1

ammonia-nitrogen concentrations increased to a maximum of 4060

R2

ammonia-nitrogen concentrations increased to a maximum of 4550

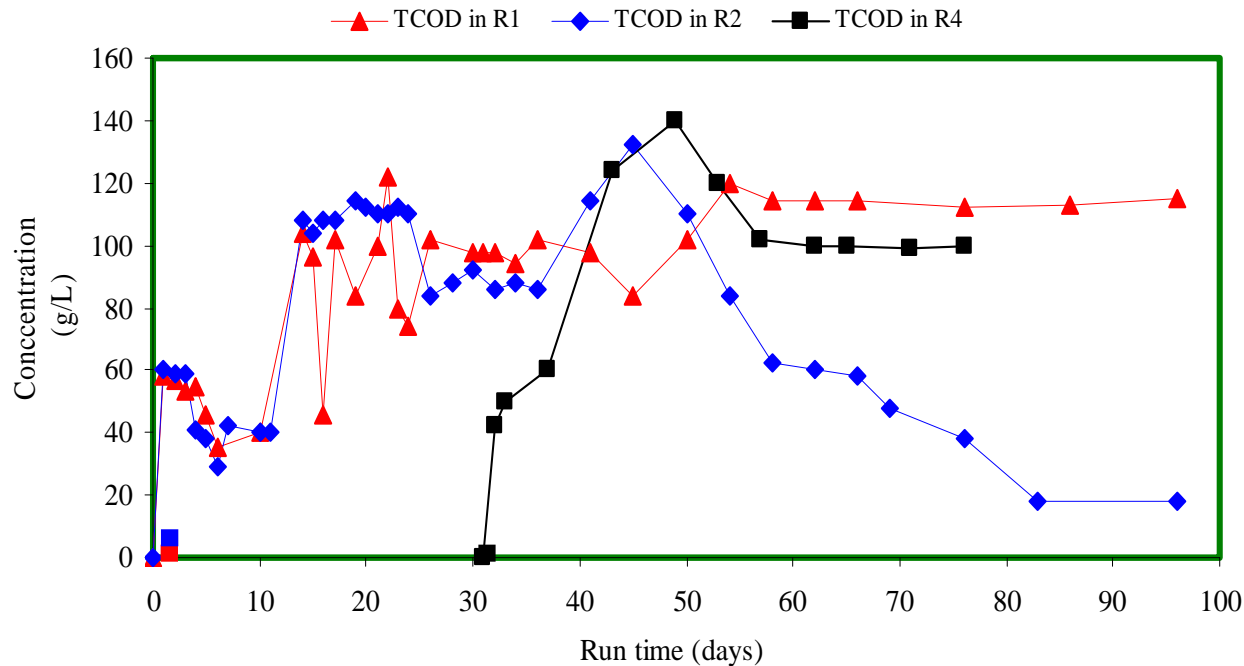
R4

ammonia-nitrogen concentrations increased to a maximum of 3710



Results and Discussions (cont..)

COD concentration



R1

COD concentration in leachate steady remained 100g/L after 54 days

R2

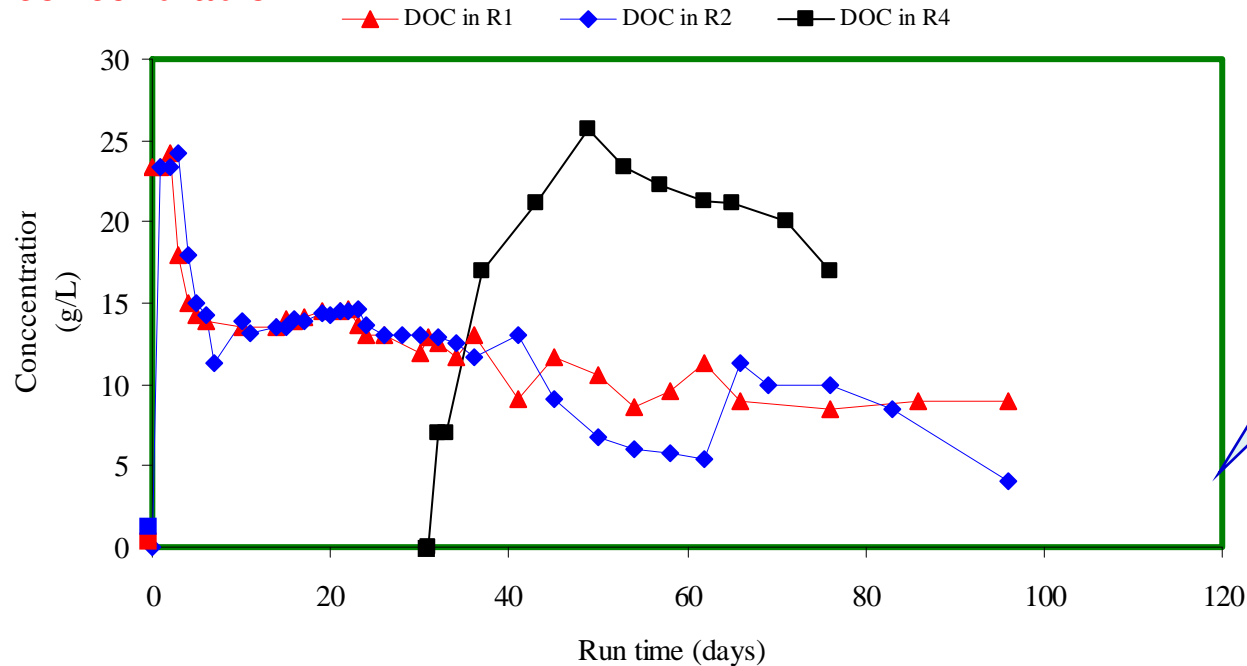
COD concentration in leachate dropped dramatically to below 84 g/L on day 54.

R4

COD concentration in leachate was around 100g/L after 45 days

Results and Discussions (cont..)

DOC concentration



•Liquefaction of organic solid waste is limited by hydrolysis of particulate material (Easteman and Ferguson et al.,1981)

R1

DOC concentration was 14.1 after 19 days

R2

DOC concentration was 14.4 after 19 days

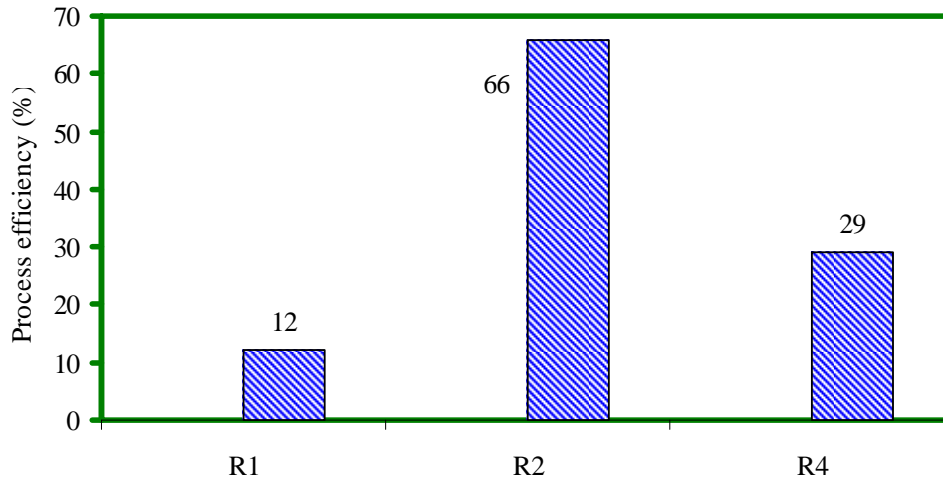
R4

DOC concentration was 25.7 after 19 days



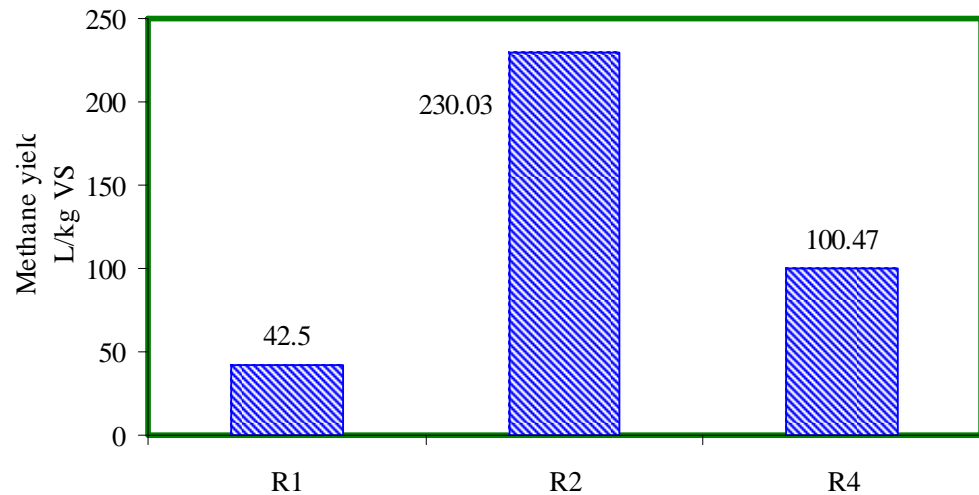
Results and Discussions (cont..)

Overall SEBAC process assessments



Compared with Kim (2003), Griffin (1998) had reached similar value of specific methane yield (240-290m³ CH₄/ton TVS added)

It can be noticed that the differences upon the composition of different substrates used in each country or type of technology may justify the different values for specific methane yield.

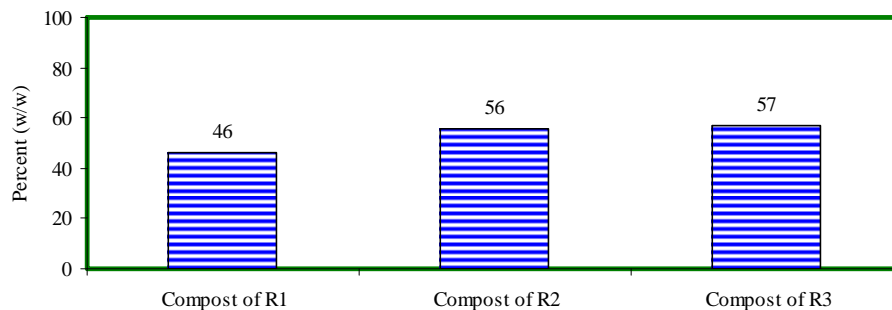




Results and Discussions (cont..)

Windrow composting

Parameter	Digested sludge from R1	Digested sludge from R2	Digested sludge from R3	Optimum Condition (EPA, 1994)
Nitrogen (% DW)	1.8-2	1.8-1.9	1.8-1.9	1
pH	7.8	8.1	8.3	7-7.5
Moisture (%WW)	60	78	78	40-60%
C/N	19	17	15	20-25
P (% DW)	0.58	0.54	0.51	1



Moisture content of compost in R1,R2 and R3 reduced 46, 56 & 57% respectively



Conclusions

Circulation of leachate within reactor produced about 5 time more methane than the reactor without circulation of leachate indicating that leachate circulation has a positive effect on methane recoveries.

Biogas production was strongly dependent on and very sensitive to the fluctuation of ambient temperature.

The specific methane yields in three reactors were;

- 42 L CH₄ /kg VS in 96 days with 12 % efficiency (no-circulation leachate),
- 230 L CH₄ /kg VS in 96 days with 66 % efficiency (direct circulation of leachate) and
- 100 L CH₄ /kg VS in 45 days with 29 % efficiency (exchange of leachate)

Exchange leachate is a feasible method for small pilot scale treatment of biodegradable solid wastes



Recommendations

The Anaerobic digestion should further investigate on effect of indirect circulation in SEBAC

The nitrogen transformations during the pretreatment of municipal solid waste by windrow composting should be studied.



Thank you very much!!!