DRY CONTINUOUS ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN THERMOPHILIC CONDITIONS

by

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Abstract

The anaerobic digestion of municipal solid waste is a process that has become a promising technology in waste management throughout the world. Thus, the objective of this study was to optimize the applications of anaerobic digestion to the treatment of municipal solid wastes. To achieve this, the pilot scale experiment was conducted in inclined type plug flow reactor.

Initially OFMSW was digested successively in start-up process to acclimatize the reactor. Firstly, the reactor was operated in mesophilic condition (37^oC) and was shifted to thermophilic (55^oC) condition by gradually increasing the temperature at the rate of 2 ^oC per day. The start-up process was established over a period of 8 weeks and the highest volume of biogas production (791L/d) and methane composition (66%) was achieved at day 38.

Dry continuous anaerobic digestion of source-sorted OFMSW was investigated in thermophilic condition with three different organic loading rates (OLR) of 2.5, 3.3 and 3.9 kg VS/m^3.d for constant retention time of 25 days. The reactor showed stable performance with highest biogas yield (278.4 L CH_4/kg VS) with VS reduction of around 59.21% during loading rate 1. However, the biogas yield and VS reduction during loading rates 2 and 3 were found relatively less than the loading rate 1. The result showed the accumulation of VFA which is the inhibiting conditions for methanogenic activity which was confirmed by the decreased of pH below 6.5 during theses loading rates.

In this study, the post-treatment of the fresh digestate was done to increase the TS concentration thereby decreasing the weight and volume of fresh digestate for the transportation as well as made suitable for composting or soil amendment. The results obtained during post refining process shows that the high increase of the TS concentration was achieved during the retention time of 15 days as well as the decrease in the pollutant loads of the percolate (leachate). Similarly, the nutrient contents and calorific value (12.1 MJ/kg DW) of the digestate showed that they are well within the WHO and Thailand standards. So they can be used as fertilizer as well as for refuse derived fuel (RDF). This study also confirmed about the energy production and consumption within the system itself and found about 80 % surplus energy from this system.

Table of Contents

Chapter	Title	Page
	Title Page	i
	Acknowledgements	ii
	Abstract	iii
	Table of Contents	iv
	List of Tables	vi
	List of Figures	vii
	List of Abbreviations	viii
1	Introduction	1
	1.1 Background	1
	1.2 Problem statement	2
	1.3 Objectives of the study	3
	1.4 Scope of the study	3
2	Literature review	4
	2.1 Introduction	4
	2.2 Solid waste generation and its characteristics in Asian countries	5
	2.3 Potential problems associated with landfills	6
	2.4 Pretreatment of waste prior to landfills	8
	2.5 Integrated solid waste management and sustainable development	9
	2.6 Energy potential of municipal solid wastes	10
	2.7 General AD process description	11
	2.7.1 Pretreatment of feedstock	12
	2.7.2 Anaerobic digestion process	13
	2.8 Types of anaerobic digestion systems	15
	2.8.1 Continuous versus batch process	16
	2.8.2 Mesophilic versus thermophilic digestion	17
	2.8.3 Single stage versus multi stage digestion	18
	2.9 Factors affecting operation of AD process	19
	2.9.1 Waste composition/volatile solids (VS)	19
	2.9.2 Alkalinity and pH	20
	2.9.3 Volatile fatty acids concentration	20
	2.9.4 Temperature	20
	2.9.5 C/N ratio	21
	2.9.6 Retention Time (RT)	22
	2.9.7 Organic Loading Rate (OLR)	22
	2.9.8 Mixing	23
	2.10 Current status of AD treatment processes	23
	2.11 Post treatment of residual fraction from AD	27
	2.12 Co-digestion of OFMSW	28
3	Methodology	29
	3.1 Introduction	29
	3.2 Pilot scale continuous digestion system	29
	3.2.1 Design of the digester	29
	3.2.2 Experimental procedure	32

	3.3 Determination of methane potential of organic wastes	35
	3.3.1 Procedures for measuring methane potential	35
	3.3.2 Equipment and supplies for BMP test	36
	3.3.3 Important of BMP test	37
	3.4 Sampling and analytical procedure	37
	3.4.1 Solid waste analysis	37
	3.4.2 Nutrient analysis	39
	3.4.3 Biogas analysis	39
	3.4.4 Leachate characteristics analysis	40
	3.5 Post- treatment of digestate	40
	3.6 Energy balance of the process	42
4	Results and Discussions	44
	4.1 Waste segregation in AIT	44
	4.2 Continuous anaerobic digestion reactor	45
	4.2.1 Feedstock preparation and analysis	45
	4.2.2 Phase 1: Reactor start-up	46
	4.2.3 Phase 2: Continuous feeding	50
	4.2.4 Overall process performance	54
	4.3 Post-treatment of digestate	55
	4.4 Digestate quality	56
	4.5 Biochemical Methane Potential (BMP) test	57
	4.6 Mass balance	59
	4.7 Energy balance	59
	4.8 Conceptual framework for AIT solid waste management	61
5	Conclusions and Recommendations	64
	5.1 Conclusions	64
	5.2 Recommendations	65
	References	66
	Appendices	71
	Appendix A Photograph	72
	Appendix B Sample calculation	73
	Appendix C TC and IC standard curves	77
	Appendix D Pilot scale-continuous anaerobic digestion	78
	Appendix E Solid waste characteristics of fresh and digested waste	86
	Appendix F Solid waste generation	87
	Appendix G Sample calculation for post treatment	88
	Appendix H Sample calculation for conceptual AD plant	89
	Appendix I BMP data in lab scale	90

List of Tables

Table	Title	Page
2.1	Urban MSW generation	5
2.2	Comparison of aerobic composting and anaerobic digestion	9
2.3	Fractions in MSW and treatment options	10
2.4	Typical biogas composition	11
2.5	Advantages of anaerobic digestion process	11
2.6	Mesophilic and Thermophilic Anaerobic Digestion	17
2.7	Inhibitors of biomethanization	21
2.8	Typical C/N ratio for various materials	22
2.9	Methane yield from OFMSW	24
2.10	Comparison of different AD systems	25
3.1	Pilot scale experimental reactor runs	35
3.2	General information on nutrient analysis	39
3.3	Leachate characteristics analysis	43
4.1	Characteristics of raw shredded solid waste and inoculums	46
4.2	Characteristics of solid waste during continuous loadings	46
4.3	Nutrient analysis in feedstock	46
4.4	Loading schemes for continuous operation	50
4.5	Nutrient analysis of digestate	57
4.6	Mass balance system	59
4.7	Energy balance system	60
4.8	Simulation of pilot-scale plant with actual plant	62

List of Figures

Figure	Title	Page
2.1	Composition of urban solid waste in Asian countries (Mendes & Imura, 2004)	6
2.2	State of MSW disposal methods in Southeast Asia (UNEP, 2004)	7
2.3	Anaerobic digestion process (Evans, 2001)	13
2.4	Classification of anaerobic digestion by operational criteria (Evans, 2001)	16
2.5	Comparisons between Mesophilic and Thermophilic AD Plants in Europe (Verma, 2002)	18
2.6	Comparison between Single Stage (SS) and Multi Stage (MS) AD plants in Europe (Verma, 2002)	19
3.1	Diagram of research methodology	30
3.2	Detail design of pilot scale dry continuous anaerobic digestion system	31
3.3	Material balance analyses in AD process	33
3.4	The detail procedure of BMP test (Hansen et al., 2004)	36
3.5	Material balance of anaerobic digestion system	38
3.6	Sludge drying bed: Plan view	41
3.7	Sludge drying bed: Cross-sectional A-A view	41
4.1	Organic waste generation from selected sources in AIT	45
4.2	Daily and Cumulative biogas production during start-up	47
4.3	Trend of biogas composition during reactor start-up	48
4.4	Variation between pH and alkalinity	48
4.5	Trend of VFA concentration and pH	49
4.6	Variation of COD and DOC during star-up operation	49
4.7	Trend of NH4-N and TKN during start-up process	50
4.8	Daily and cumulative biogas production during Loading rate 1, 2 and 3	51
4.9	Variation of biogas compositions during loading rates 1, 2 and 3	51
4.10	pH and Alkalinity during continuous feeding	52
4.11	Variations of COD and DOC	53
4.12	TKN and NH4-N during continuous feeding	53
4.13	Profile of specific methane production for various loading rates	54
4.14	VS degradation for various loading rates	55
4.15	Cumulative methane production curves measured for OFMSW and blank	58
4.16	Specific methane production curve for OFMSW	58
4.17	Mass balance system during loading rate 1	59
4.18	Energy consumed in continuous AD system	60
4.19	energy balances in AD system	61
4.20	Conceptual flow diagram of organic fraction of AIT solid waste	61
4.21	Layout of the AD plant for AIT solid waste	63

List of Abbreviations

AD	Anaerobic Digestion
AIT	Asian Institute of Technology
BMA	Bangkok Metropolitan Administration
BMP	Biochemical Methane Potential
BMSW	Biodegradable Municipal Solid Waste
COD	Chemical Oxygen Demand
C/N	Carbon to Nitrogen ratio
CSTR	Continually Stirred Tank Reactor
DCAD	Dry Continuous Anaerobic Digestion
DC	Developing Countries
DOC	Dissolved Organic Carbon
DRANCO	Dry Anaerobic Composting
EU	European Union
GC	Gas Chromatograph
HS	High Solids
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectroscopy
ISWM	Integrated Solid Waste Management
KWH	Kilo Watt Hour
LFG	Landfill Gases
LS	Low Solids
MBT	Mechanical Biological Treatment
MC	Moisture Content
MS	Multi Stage
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid waste
OLR	Organic Loading Rate
OM	Organic Matter
RT	Retention Time
RVS	Refractory Volatile Substance
SDB	Sand Drying Bed
SRT	Solid Retention Time
SS	Single Stage
SS-OFMSW	Source-Sorted Organic Fraction of Municipal Solid Waste
STP	Standard Temperature Pressure
SWM	Solid Waste Management
TOC	Total Organic Carbon
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solid
UNEP	United Nation Environmental Programme

Chapter 1

Introduction

1.1 Background

Due to upward trend in energy costs and problems associated with incineration of municipal solid wastes (MSW), there have been developed many technologies that can partially solve the problems. Biological conversion of biomass to methane has received increasing attention in recent years (Gunaseelan, 1997).There are many renewable technologies for producing the energy from the solid wastes such as anaerobic digestion, incineration, Refuse Derived Fuel (RDF) etc. among them the conversion of wastes to energy by Anaerobic Digestion (AD) has become an interesting technology and many research works are going on for the stability of this system. Since last two decades, anaerobic treatment technology had been in practice but those techniques were based on mainly for treating wastewater sludge with low solid concentration. The anaerobic digestion of MSW is a process that has become a major focus of interest in waste management throughout the world. During the last two decades, considerable progress has been occurred in understanding the anaerobic process.

Rapid economic growth by industrialization of the developing countries in Asia, uncontrolled and unmonitored urbanization have created serious problems of solid waste disposal. Many cities of the Developing Countries (DC) are facing problems with municipal solid wastes that comprise of high fraction of putrecible organic wastes that can easily be degraded and causes the serious environmental and health risks. Currently, biological treatment methods such as composting and AD offer the only route for recycling organic matter and nutrients from organic fraction of MSW (Braber, 1995).

Most of the anaerobic digestion plants are operating in Europe (91%), with some in Asia (7%) and a few in the US (2%). Germany is the leader with 35% of all AD plants, followed by Denmark (16%), Sweden, Switzerland, and Austria (8%) (Verma, 2002).The technology has good commercial acceptance as the trend of the development of this technology is in increasing order. One attractive application of anaerobic digestion is for treating municipal solid wastes in order to reduce the wastes to be disposed and to produce renewable energy. Solid wastes in DCs have become great problem because the amounts of the solid wastes are increasing day by day due to rapid population growth and urbanization. The availability of landfill sites are declining due to conventional disposal methods and the opening of new landfill sites are limited due to legal and financial problems.

Since the municipal solid wastes consist of high proportion of organic fraction and it is understood as organic-biodegradable waste with moisture content around 85 -90 %. These wet streams of wastes are not so viable for incineration to produce energy. The incineration generates the air pollutants such as nitrogen dioxide, sulfur dioxide and greenhouse gases. Around the world particularly in urban areas, pollution of air and water from municipal solid wastes continues to grow. It has become great threat to environmental and public health. Anaerobic digestion not only provides pollution prevention, but also allows for energy, compost and nutrient recovery. In life cycle assessment using eco-indicator method, AD also showed an excellent LCA performance compared to other treatment technology such as composting, incineration (Edelmann et al., 2004).

Anaerobic digestion is an engineered methanogenic decomposition of organic matter in the absence of free oxygen and involves a consortium of different anaerobic microorganism which transforms organic matter into useful energy. Application of anaerobic digestion for waste treatment produces significant benefits that include both energy production and energy conservation (Wilkie, 2005). The production of biogas from solid waste materials for using as a fuel source succeeds anaerobic digestion as a sustainable technology for renewable energy source. The anaerobic digestion of the Organic Fraction of Municipal Solid Wastes (OFMSW) yields much better results in thermophilic temperature conditions than in mesophilic temperature conditions.

In the early days, application of anaerobic digestion was for the treatment of domestic and animal wastes. Presently, the process is using widely for treatment of municipal sludge and industrial wastes in developed countries. Due to alarming threatening on municipal solid wastes management for final disposal, municipalities are looking for better solution and many research works are going on anaerobic digestion for its stable operation on treating organic fractions of MSW. Both source separation and recycling have attracted increasing attention. Consequently, separate fractions of MSW are becoming available for more advanced treatment prior to disposal or recycling.

In the absence of strict environmental regulations for municipal solid wastes and prevailing low prices of other non-renewable energy, the development of AD technology has been decelerated. But with the advancement of researches on anaerobic digestion of municipal solid waste, the technology is accelerating for the sustainable disposal of solid wastes in integrated solid waste management.

1.2 Problem statement

A given amount of volatile solids of a particular waste can be converted to a maximum amount of biogas at a given temperature provided optimum conditions are prevalent. This conversion can be accounted by two factors i.e. biodegradability at a specified temperature and operating conditions that depend on kinetics, reactor configuration, the flow pattern within the digester, digestion stage as well as the presence of the inhibitory substances such as Volatile Fatty Acids (VFA) and ammonia concentration .

It is difficult to summarize on anaerobic digestion of solid waste with similar experimental set up. This difficulty is due to the great diversity of reactor designs which is suited by a large variation of waste composition and choice of operational parameters such as retention time, solid contents, mixing, recirculation , number of stages, temperature etc. The evaluation of the reactor designs can be made in terms of the rate, stability and completion of biochemical reactions as well as emissions of pollutants and recovery of energy or materials. The biomethanization of organic wastes is accomplished by a series of biochemical transformations, which can be mainly separated into two steps. The first step consists of hydrolysis, liquefaction and acidification whereas the second step involves the transformation of acetate, hydrogen and carbon dioxide into methane. One of the major issues regarding with the stability of an anaerobic digestion process is bacterial nutritional requirements because insufficient nutrients may result in an incomplete, unstable bioconversion of the organic wastes and may ultimately cause digester failure (Kayhanian & Rich, 1995).

Depending upon the number of stages and concentration of total solids, the design of reactor is classified as single stage wet or dry system and multi stage wet or dry system. Similarly the anaerobic rectors can be operated into different modes i.e. batch system, semi- batch system and continuous system. In the batch system the fresh wastes to be treated are filled into the reactors together with the necessary inoculums and are sealed. Then the wastes are permitted to digest without any interference until the complete digestion occurs. In case of semi-continuous digestion system, the feedstocks are fed on a more frequent basis, usually once or twice a day and the digested materials are removed simultaneously. Such types of AD system are particularly suited to a regular and steadily arising waste stream. In continuous system feeding and withdrawing of wastes happens in as unbroken cycle. The wastes are fed little by little and the digestion takes place uninterrupted.

According to previous studies done by Eliyan (2007), there was a problem of low biogas yield, low methane composition and lower removal of volatile solids in the continuous anaerobic digestion system operating in thermophilic range. The problem was due to the design configuration of the reactor. In this study the problems as said above has solved by modifying the design of reactor and the optimization of operational parameters such as organic loading rates, retention time for maximum volatile solids reduction has conducted.

1.3 Objectives of the study

The main objective of this research is to employ anaerobic digestion process as a sustainable technology for minimizing the organic fraction of municipal solid waste going to landfill and to provide the renewable source of energy as well as to reduce the potential greenhouse gases emission from landfill. The specific objectives of this study are as follow:

1. To optimize the methane yield of OFMSW with different organic loading rates in thermophilic condition;
2. To analyze the operational parameters for the stability of Dry Semi-continuous Anaerobic Digestion (DSAD) system;
3. To investigate the mass and energy balance in AD system;
4. To analyze biodegradability of organic materials by Biochemical Methane Potential (BMP) test.

1.4 Scope of the study

- The source-sorted organic fraction of solid wastes were collected from Asian Institute of Technology (AIT);
- The digester was operated in high solid single stage semi-continuous mode of operation.
- Inoculums were comprised of anaerobic sludge from wastewater treatment plant, cow dung and digested material from AD of municipal solid wastes;
- The average particle size of 10 mm was used and was operated at temperature of 55 ^{o} C.
- The methane potential of solid wastes was determined in laboratory scale by using BMP test.

Chapter 2

Literature review

2.1 Introduction

Rapid population growth, industrialization and urbanization have inflamed the problems associated with management of municipal solid waste. Ineffective and inappropriate solid waste management is responsible for numerous problems such as environmental pollution, low level of sanitation, unhygienic living conditions etc. Although in the last few years, there has been a reduction in the percentage of wastes being disposed, landfilling remains the prevailing option in many European Union (EU) countries. The landfill Directive (EU) promotes the reduction of wastes that are landfilled and requires that by 2016, Biodegradable Municipal Solid Waste (BMSW) going to the landfill must be reduced to 35% of the total amount by weight of BMSW produced in 1995 (Garcia et al., 2005).

The improper handling of MSW during its collection, storage and transportation poses serious environmental and public health effects. Many landfills in DCs are not well-engineered design due to lack of expertise and resources. For example, surface water around the On-nooch disposal site, the Bangkok Metropolitan Administration's (BMA) biggest solid waste disposal site, was shown to be polluted by leachate. Organic matter, nitrogen and heavy metals were detected at higher levels than allowable (Chaya and Cheewala, 2007) in the landfill sites. Due to these problems, sound and sustainable methods of solid waste management are essential for proper disposal of organic fraction of MSW.

To reduce the volume of waste going to landfill sites, the pre-treatment is essential and there are many pre-treatment technologies such as composting, Mechanical Biological treatment (MBT), anaerobic digestion, incineration etc. Incineration, which mainly focuses on the energy value of waste materials, is not a sustainable solution. Due to the composition of waste such as high proportions of vegetable and putrecible matter and the high investment and operating costs of the sophisticated technology, incineration is rarely a viable option for waste treatment in many mega-cities of DCs. Landfill gases recovery and utilization might be a more promising approach to energy recovery. The major problems of final disposal of waste in most of the cities in DCs are the public and environmental health risks as the landfill sites are operated in uncontrolled manner and environmentally unsound dumps.

Anaerobic digestion is an attractive option for treatment of the putrecible fraction of MSW because it produces CH_4, which is a fuel. Due to relatively high moisture content of food waste, bioconversion technologies, such as anaerobic digestion, are more suitable compared to thermochemical conversion technologies, such as combustion and gasification. The aim of this chapter will be to review the status of solid wastes generation in developing countries and its characteristics, disposal methods of MSW, pretreatment of wastes going to landfill, energy potential of MSW, and overall anaerobic digestion process for treating organic fraction of MSW and will also include the post treatment option.

2.2 Solid waste generation and its characteristics in Asian countries

Increasing urbanization and economic development in developing countries have greater impact on management of society's solid wastes. Today, the urban areas of Asia produce about 760,000 tones of MSW per day. In 2025, this figure will increase to 1.8 million tones of waste per day (World Bank, 1999). These estimates are conservative and the real values are probably more than double this amount.

Solid waste streams should be characterized by their sources, by the types of wastes produced, as well as by generation rates and composition. Accurate information in these three areas is essential in order to monitor and control existing waste management systems and to make regulatory, financial, and institutional decisions. Waste generation rates are affected by socioeconomic development, degree of industrialization, and climate. Table 2.1 shows the urban MSW generation in low and middle income countries.

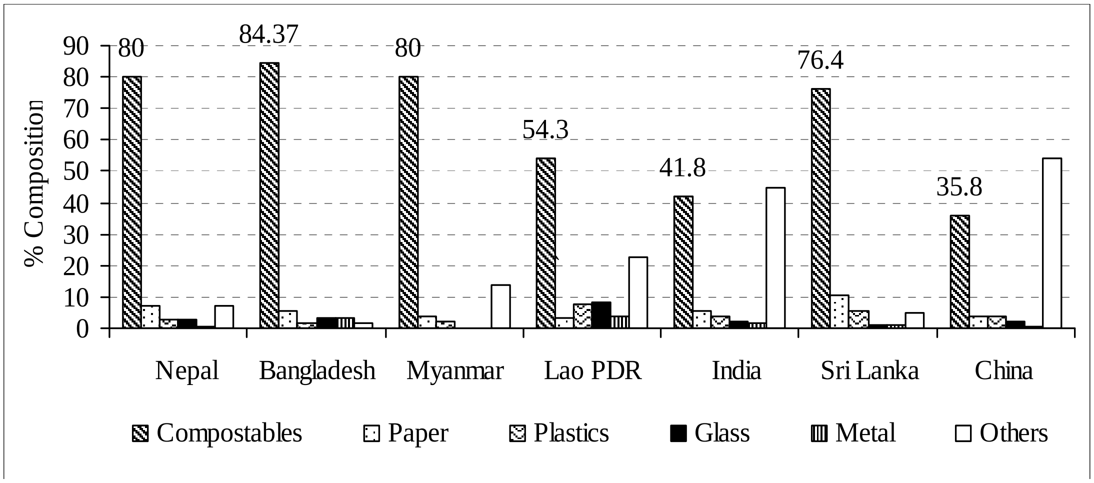
Table 2.1 Urban MSW generation

Country	Urban MSW generation (kg/capita/day)
Nepal	0.50
Bangladesh	0.49
Myanmar	0.45
Vietnam	0.55
Mongolia	0.60
India	0.46
Lao PDR	0.69
China	0.79
Sri Lanka	0.89
Indonesia	0.76
Philippines	0.52
Thailand	1.10
Malaysia	0.81

Source: World Bank, 1999

Many cities in developing countries are facing a serious problem in managing their solid wastes. The annual waste generation increases in proportion to the rise in population and urbanization, and issues related to disposal have become challenging as more lands are needed for the disposal of increased solid wastes.

Generally, all low and middle income countries have a high percentage of degradable organic matter in the MSW stream, ranging from 40 to 85 percent of the total. A comparison of the current waste composition in Asian countries is shown in Figure 2.1. These figures represent that, about 70% or more (by weight) of the waste is combustible (i.e. organics, paper and plastics) in least developed Asian countries, apart from China where there is a high percentage of ash. The composition of MSW stream in Asian cities shows high (>50%) biodegradable organic fraction (Visvanathan et al., 2004). However, the composition differs depending on the economic level of cities as well as other factors such as geographic location, energy sources, climate, living standards and cultural habits,



and the sources of waste that are considered as MSW or are collected by the municipality.

Figure 2.1 Composition of urban solid waste in Asian countries (Mendes & Imura, 2004)

2.3 Potential problems associated with landfills

The present disposal methods for MSW in most Asian cities are generally open dumping that are associated with water pollution and public health problems. Upgrading open dumps into properly managed, environmentally acceptable landfill sites must be the first priority to eliminate the problems. Conversion of open dumps into sanitary landfills may be very difficult in practice due to the lack of suitable sites, potential water pollution problems, shortages of cover material and the presence of scavenger communities who depend for their livelihood on the waste.

Proper solid waste disposal is an important component of environmental sanitation and sustainability of solid waste management. A sustainable management of solid wastes offers opportunities for income generation, health improvements and reduced vulnerability. At present, most of the BMSW is disposed of in landfills. But this practice has a negative affects on the environment so it is necessary to find and to apply alternative treatment methods to these waste stream in order to divert it from landfill. Composting, anaerobic digestion, incineration, thermolysis and gasification etc are the most usual pre-treatment methods. But the implication of the method depends upon many factors such as waste characteristics, availability of land, location of the treatment sites etc.

Waste quantities are increasing at an alarming rate. Countries with rapid economic growth in Asia such as China and India are already struggling with the proper disposal of large quantities of solid waste. The methods of disposing MSW waste in Southeast Asian countries are shown in Figure 2.2. Many low income countries lack the facilities for safe disposal. The current practices in most of the low income countries are uncontrolled dumping and it might take more than 20 years to provide sanitary disposal of municipal solid waste. Anaerobic fermentation in landfills extends for periods of 20-40 years and it takes decades to reach 50% methane content (Vieitez et al., 2000). It has been estimated that groundwater pollution originating from landfills may be at risk after several centuries (Ludwig et al., 2003).

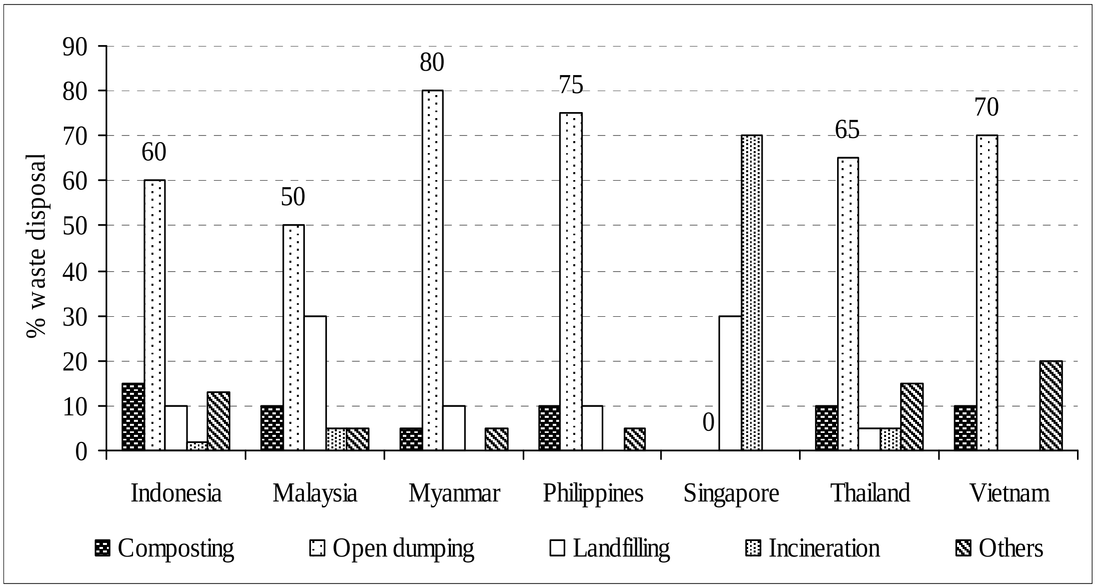


Figure 2.2 State of MSW disposal methods in Southeast Asia (UNEP, 2004)

The disposal of MSW has always been a difficult problem throughout the world. Landfillings, especially in DCs, are primarily open dumps without leachate or gas recovery systems. Several landfill sites are located in ecological or hydrologically sensitive areas. They are generally operated below the recommended standards of sanitary practice. The facilities are sub-standard and unsafe which pose public health risks and aesthetic burdens to the people for whom they are served.

The problems associated with landfills, even with those that are clay-lined, include high water table, groundwater contamination and greenhouse gases migration. High percentages of organics and plastics have led to breakouts of fire due to methane gas generation, e.g. in Bangkok and Manila (UNEP, 2004). The problems with landfill disposal are summarized as below:

- Need for a site
- Risk of land and water pollution
- Noise pollution, visual pollution and the attraction of vermin
- Contribution to global warming
- Increased demand on natural resources and energy
- Economically expensive

Depending on local conditions, eating and drinking habits, climate, and the degree of industrialization, between 60% and 70% of MSW consists of BMSW (food and green waste and paper and cardboard waste) (Garcia et al., 2005). Landfill sites are usually constructed out of town on green field sites and therefore have detrimental affects with the loss of another piece of natural environment. Landfill sites also run the risk of leaking chemicals, heavy metals and bacteria into the soil and water table, while organic wastes in particular can cause problems by degrading to form leachate - a highly polluting liquid, despite of construction of high safety regulations.

Due to problems associated with noise and visual pollution, the potential of providing breeding sites for vermin and disease as well as unpleasant odors of degradable materials, it is very difficult to locate the site in nearby community area. Degradation of organic waste in the sites produces methane (CH_4) and carbon dioxide (CO_2) as by-products of decomposition process. Both these gases are significant contributors to global warming leading to breakdown of the stratospheric ozone layer and the subsequent dramatic climatic changes.

Disposal of recyclable wastes such as glass, plastic, paper, cardboard, textiles, metals in landfill sites create the ever increasing demand for raw materials and depleting the world's non-renewable natural resources. Disposing the wastes in the landfill is economically expensive due to high collection and transportation costs.

2.4 Pretreatment of waste prior to landfills

Several types of pre-treatment processes are available and the selection must be done regarding prices, feedstock, and process operations. Conventional solid waste disposal techniques have limitations throughout the world with increasing waste generation and rising proportions of packaging and toxic compounds in MSW. Furthermore, it is increasingly more difficult to find suitable locations for landfills which are accepted by the people living around in many countries. The promotion of waste minimization and recycling are important components of modern waste management strategies. Even when the minimization and recycling potentials are fully exploited, there is still some residual fraction which has to be disposed of into landfill. The burdens resulting from landfilling can be minimized by pre-treating the waste and thus limiting its emission potential (Fricke et al., 2005). Mechanical pretreatment reduces volume and increase specific surface area of the waste materials. As a result, the performance of biological pretreatment step is enhanced and stabilized (Leikam & Stegmann, 1999). The following options are available for residual waste treatment:

- Mechanical Biological Treatment (MBT) of residual waste, with or without inclusion of anaerobic digestion technology.
- Thermal waste treatment
- Energy utilization of fuels from residual waste

The objectives of pretreatment of the wastes going to landfill are;

- Minimization of landfilled masses and volume,
- Inactivation of biological and biochemical processes in order to avoid landfill gas and odor emissions; at the same time landfill settlements are reduced, and
- Immobilization of pollutants in order to reduce leachate contamination.

To fulfill the above mentioned objectives for pretreatment of solid wastes, anaerobic digestion technology has established as promising and suitable option. The pretreatment technologies such as aerobic composting and anaerobic digestion are compared in Table 2.2.

Table 2.2 Comparison of aerobic composting and anaerobic digestion

Aerobic composting	Anaerobic digestion
• Decomposition of organic matters in the presence of oxygen • Low quality of compost • Net energy consuming process • End products are humus, CO_2, H_2O • Larger land area is required	• Biological breakdown of organic materials in the absence of oxygen • High quality of compost • Net energy producing process • End products are sludge, CO_2, CH_4 • Relatively less land area is required

2.5 Integrated solid waste management and sustainable development

Based on the concept of the waste management hierarchy as the preferred approach for managing MSW, Integrated Solid Waste Management (ISWM) can be defined as the selection and application of suitable techniques, technologies and management programs for achieving specific waste management objectives and goals. Clearly, reduction, reuse and recycling practices can be valuable approaches to achieve a certain level of sustainability. However, practical experiences are demonstrating that there are some limitations to extent these options which can manage the waste in an environmentally sound, practical and cost effective manner. Worldwide attempts for the conservation of resources and the protection of the atmosphere started about fifteen years ago. The 1987 Report of the World Commission on Environment and Development made a strong case for sustainable development. The importance of environmental protection is emphasized as the conservation of the limited resources e.g. soil, water, air, energy, and raw materials is a problem of the entire world. Waste management takes the key position towards a sustainable development. Accordingly the efforts to reduce the consumption of non-renewable resources are generally linked with the reduction of waste.

A widely used and accepted international definition of sustainable development is 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. The increasing stress we put on resources and environmental systems such as water, land and air cannot go on forever. Especially as the world's population and economic activities continue to increase and we have already seen a world where over a billion people live on less than a dollar a day. Table 2.3 shows that how AD can be integrated into general MSW management in which the application of treatment options for different fractions of wastes are mentioned.

Table 2.3 Fractions in MSW and treatment options

	Organic fraction	Paper fraction	Plastic fraction
Source separation	• AD for energy and refuse • composting	• recycling • digestion	• Recycling • incineration
Mechanical separation	• AD for energy and refuse • Incineration • Composting • landfill	digestion	• Incineration • recycling
Commingled MSW	• Incineration • landfill	• Incineration • landfill	• Incineration • landfill

Source: Braber (1995)

Processing biodegradable waste using anaerobic digestion helps to reduce global warming. The carbon in biodegradable waste is part of a complete carbon-cycle: the carbon released from the combustion of biogas was removed by plants in the recent past, and does not contribute to the global accumulation of carbon in the same manner that fossil fuels do. Anaerobic digestion was also seen to have more potential for nutrient enrichment than incineration because of the high ammonia emission to water. The avoided impact from fertilizer production could not offset the gross impact. For incineration, gases such as NO_X from waste combustion contributed much of the impact. Furthermore, if this waste is landfilled, it would break down naturally and the biogas would escape directly into the atmosphere. Using the biogas for energy is an intermediate use that does not affect the overall cycle. In this way anaerobic digestion of biodegradable fraction of MSW is considered to be a sustainable technology and biogas is considered to be a renewable fuel. The fundamental need for society is to minimize waste production, and to protect health by effectively managing the wastes that are inevitably generated by human activity.

2.6 Energy potential of municipal solid wastes

The compromise between the energy and the environment is a recent controversial issue. Generally, people assume that energy generation and environmental protection activities contradict each other. More clearly, most of the energy generation systems exploit the natural resources and are a hazard to the environment in terms of source depletion and environmental contamination. One of the solutions of this problem is to implement synergy between environmental protection and energy generation

There are many areas in environmental technologies that facilitate both waste treatment and energy generation in a cycle. Solid waste is one of the typical examples of energy recovery systems. There are various options available to convert solid waste to energy such as incineration, sanitary landfill (landfill gas), gasification, pyrolysis, anaerobic digestion, and others. All these technologies have their own merits and demerits. The choice of the technology should be based on the local and socio-economic conditions as well as waste quality and quantity. Among these AD is one of the most attractive technologies as this technology is comparatively less expensive than other methods for same energy production.

Since methane is a potentially explosive gas and is also a more effective greenhouse gas, it has to be controlled before emitting from landfill. Experiences in many countries of the world show that Landfill Gases (LFGs) can be successfully used to replace other energy sources. According to Braber (1995), the net electricity production of 100-l50 kWh per tonne of OFMSW is found which shows a large energy potential of OFMSW. Typical composition of biogas is given in Table 2.4.

Table 2.4 Typical biogas composition

Energy content	20-25 MJ/m^3
Methane (CH_4)	55-70%
Carbon dioxide (CO_2)	30-45%
Hydrogen sulfide (H_2S)	200-4000 ppm

Source: RISE-AT, 1998; Braber, 1995

2.7 General AD process description

Generally the overall AD process of OFMSW can be divided into three stages: pretreatment, anaerobic digestion, and post-treatment. There are number of benefits resulting from the use of AD technology which are described in Table 2.5.

Table 2.5 Advantages of anaerobic digestion process

Waste treatment benefits	Environmental benefits
• Natural waste treatment process • Requires less land than aerobic composting or landfilling • Reduces disposed waste volume and weight to be landfilled	• Significantly reduces carbon dioxide and methane emissions • Eliminate odor • Produces a sanitized compost and nutrient-rich liquid fertilizer • Maximizes recycling benefits • potential to treat the OFMSW in countries considering banning landfilling of waste
Energy benefits	**Economic benefits**
• Net energy producing process • Generate high quality renewable fuel • Reduce CO2 emissions, by displacement of fossil fuels • Biogas proven in numerous end-use Applications	• More cost-effective than other treatment options from a life cycle perspective

Disadvantages of AD system

- Cost: this is a major barrier, as AD is (slightly) more expensive than composting in many cases.
- AD of MSW does not treat whole waste, only a fraction of it.
- Information on economic and practical issues is not widely disseminated

- Wastewater may need to be treated before disposal
- There are persistent materials handling problems

Estimation of cost for implementing an anaerobic digestion plant for MSW is difficult because there are many factors that affect the cost and the variation in circumstances and cost between different countries. For example the following factors will have an influence on the overall treatment costs (RISE-AT, 1998):

- Energy prices
- Land prices
- Labor costs
- Energy taxes and renewable energy policy
- Construction and material costs
- Markets for the compost/soil conditioning products and prices
- Quality of compost produced

2.7.1 Pretreatment of feedstock

The pre-treatment of feedstock consists in separating the recyclable or non-digestible wastes from the municipal solid wastes. Source separation has a significant effect upon the quality of the digestate. Mechanical pre-treatment leads to a lower quality digestate. The removal of all contaminants is not possible especially for the smaller fraction such as heavy metals. The resultant fraction is thus more contaminated.

There are a variety of pretreatment processes that are chosen based on the characteristics of the incoming waste and the effects they have on digestion. Separation technologies for metals, glass and plastic are usually necessary. This section will focus on pretreatment processes unique to the AD process. The pretreatment of feedstock for AD involves:

- Providing a uniform small particle size feedstock for efficient digestion
- Removing the non-biodegradable materials
- Protecting the downstream plant from components that may cause physical damage
- Removing materials which may decrease the quality of the digestate.

Most digestion systems require pre-treatment of waste to obtain homogeneous feedstock. The preprocessing involves separation of non-digestible materials and shredding. The waste received by AD digester is usually source separated or mechanically sorted. The separation ensures removal of undesirable or recyclable materials such as glass, metals, stones etc. In source separation, recyclables are removed from the organic wastes at the source. Mechanical separation can be employed if source separation is not available and the resultant fraction is then more contaminated leading to lower compost quality. The waste is shredded before it is fed into the digester in order to enhance the digestion rate.

Chemical pretreatment changes the composition of waste by reducing particulate organic matter to soluble form i.e. proteins, fats, carbohydrates or lower molecular weight compounds. Alkalis are added to increase the pH to 8 -11 during this process. Thermal and chemical pretreatments do improve hydrolysis and promote solubilization. Ultrasonic pretreatment also has been researched to reduce retention time.

2.7.2 Anaerobic digestion process

The anaerobic digestion of organic matter is a complex process, which falls into four degradation steps. The specific microorganisms that take part in the process have different requirements on environmental conditions and moreover coexist in synergetic interactions. Figure 2.3 explains the basic steps of anaerobic digestion process.

1. Hydrolysis

An important step of the anaerobic biodegradation process is the hydrolysis of the complex organic matter. During the anaerobic digestion of complex organic matter, the hydrolysis is the first and often the rate-limiting step (Angelidaki & Sanders, 2004). Although the rate of hydrolysis is a function of pH, temperature, concentration of hydrolytic bacteria, and type of particulate organic matter, and the physicochemical properties of particulate organic substrates quantitatively affect the rate of hydrolysis (Neves et al., 2006) is not well understood.

In this process hydrolytic organisms hydrolyze complex organic matter such as proteins, poly carbonates, lipids, etc. to simple organic compounds (formate, acetate, propionate, butyrate and other fatty acids, etc.).

Complex organic compounds (Proteins, carbohydrates, lipids) *Insoluble organics* $\xRightarrow{\textit{Hydrolytic bacteria}}$ Amino acids, sugar, fatty acids *Soluble organics*

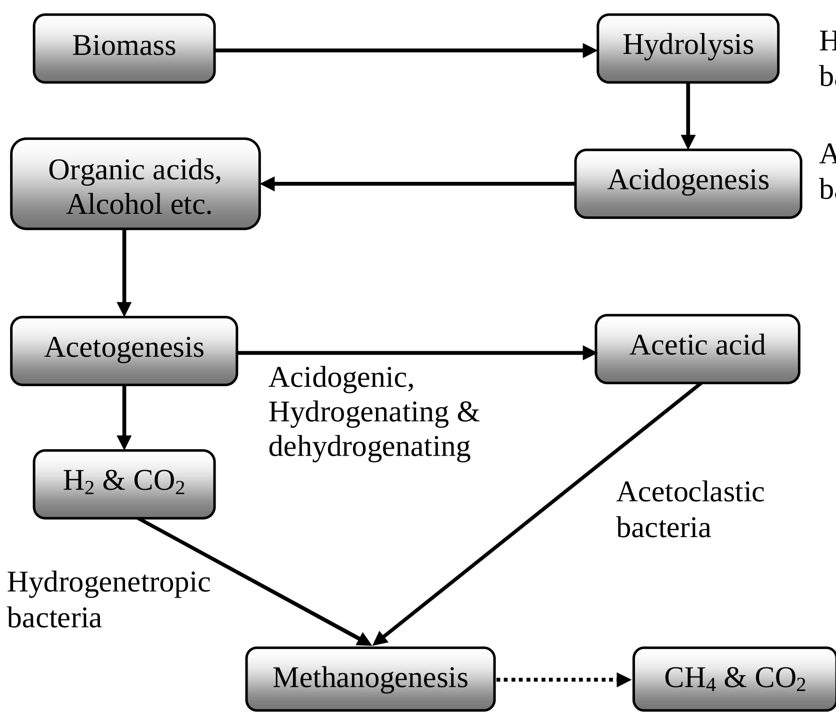


Figure 2.3 Anaerobic digestion process (Evans, 2001)

An approximate chemical formula for the mixture of organic waste is $C_6H_{10}O_4$ (Themelis, 2004). A hydrolysis reaction where organic waste is broken down into a simple sugar (glucose) can be represented by the Eq. 2.1.

$$C_6H_{10}O_4 + 2H_2O \longrightarrow C_6H_{12}O_6 + 2H_2 \qquad \text{Eq. 2.1}$$

2. Acidogenesis

In this stage, the hydrolyzed compounds are fermented into volatile fatty acids (acetic, propionic, butyric, valeric acids etc.), neutral compounds (ethanol, methanol), ammonia, and the pH falls as the levels of these compounds increases. Carbon dioxide and hydrogen are also evolved as a result of the catabolism of carbohydrates. The group of microorganisms responsible for this biological conversion is obligate anaerobes and facultative bacteria, which are often identified in the literature as acidogens.

Amino acids, sugar, Fatty acids (*Soluble organics*)	*Acidogens* $\Longrightarrow$	Intermediate compounds (propionate, butyrate, ethanol etc.)

The specific concentrations of products formed in this stage vary with the type of bacteria as well as with culture conditions such as temperature and pH (Themelis, 2004). Typical reactions in the acid-forming stages are shown below in Eq. 2.2, glucose is converted to ethanol and Eq. 2.3 shows glucose is transformed to propionate.

$$C_6H_{12}O_6 \Leftrightarrow 2\,CH_3CH_2OH + 2CO_2 \qquad \text{Eq. 2.2}$$

$$C_6H_{12}O_6 + 2H_2 \Leftrightarrow 2CH_3CH_2COOH + 2\,H_2O \qquad \text{Eq. 2.3}$$

3. Acetogenesis

The third step is acetogenesis where the simple molecules from acidogenesis are further digested to produce carbon dioxide, hydrogen and mainly acetic acid. This conversion proceeds with the action of obligate hydrogen producing acetogenic bacteria, which are considered as acetogens. The production of different by-products produced depends on the environmental conditions as described in section 2.9.

Intermediate compounds (Propionate, butyrate, ethanol etc.)	*Acetogens* $\Longrightarrow$	Acetate, carbon dioxide, and hydrogen

Acetogenesis occurs through carbohydrate fermentation in which acetate is the main product and other metabolic processes also occur. The result is a combination of acetate, CO_2 and H_2. The role of hydrogen as an intermediary is of critical importance to AD reactions. Long chain fatty acids, formed from the hydrolysis of lipids, are oxidized to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits the oxidation. The reaction only proceeds if the hydrogen partial pressure is low enough to thermodynamically allow the conversion. The presence of hydrogen consuming bacteria thus lowers the hydrogen partial pressure, which is necessary to ensure thermodynamic feasibility and thus the conversion of all the acids.

As a result, the concentration of hydrogen, measured by partial pressure, is an indicator of the health of a digester (Mata-Alvarez, 2003). The Eq. 2.4 shows the conversion of propionate to acetate. In general, it is necessary for hydrogen to have a low partial pressure for the reaction to proceed.

$$CH_3CH_2COO^- + 3H_2O \longleftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad \text{Eq. 2.4}$$

4. Methanogenesis

Methanogenesis is the last stage of anaerobic digestion which involves the production of methane from the raw materials produced in the previous stage. Methanogens which carry out the terminal reaction in the anaerobic process are the most important in anaerobic digester systems. The methane is produced from a number of simple substances: acetic acid, methanol or carbon dioxide and hydrogen. Among these, acetic acid and the closely related acetate are the most important, since around 75% of the methane produced is derived from acetate (Evans, 2001).

Methanogens can be divided into two groups: acetate consumers that utilize acetic acid known as acetoclastic methanogenesis whereas hydrogen and carbon dioxide utilizing consumers are know as hydrogenotrophic methanogenesis. The growth of methanogens is slower than the bacteria responsible for the preceding stages. This population converts the soluble matter into methane, about two thirds of which is derived from acetate conversion (Eq. 2.5 followed by Eq. 2.6), or the fermentation of an alcohol, such as methyl alcohol (Eq. 2.7), and one third is the result of carbon dioxide reduction by hydrogen (Eq. 2.8) (Themelis, 2004). It has been estimated from stoichiometric relations that about 70% of the methane is produced via the acetate pathway (Madigan et al., 2003).

$$2\ CH_3CH_3OH + CO_2 \longleftrightarrow 2\ CH_3\ COOH + CH_4 \qquad \text{Eq. 2.5}$$

$$CH_3COOH \longleftrightarrow CH_4 + CO_2 \qquad \text{Eq. 2.6}$$

$$CH_3OH + H_2 \longleftrightarrow CH_4 + H_2O \qquad \text{Eq. 2.7}$$

$$CO_2 + 4H_2 \longleftrightarrow CH_4 + 2H_2O \qquad \text{Eq. 2.8}$$

2.8 Types of anaerobic digestion systems

A wide variety of systems have been developed to anaerobically treat MSW. They can be split into different categories as following:

- Continuous versus batch process
- Mesophilic versus thermopilic digestion
- Single stage versus multi-stage digestion

Figure 2.4 depicts the classification of the anaerobic digestion system based on the operating criteria.

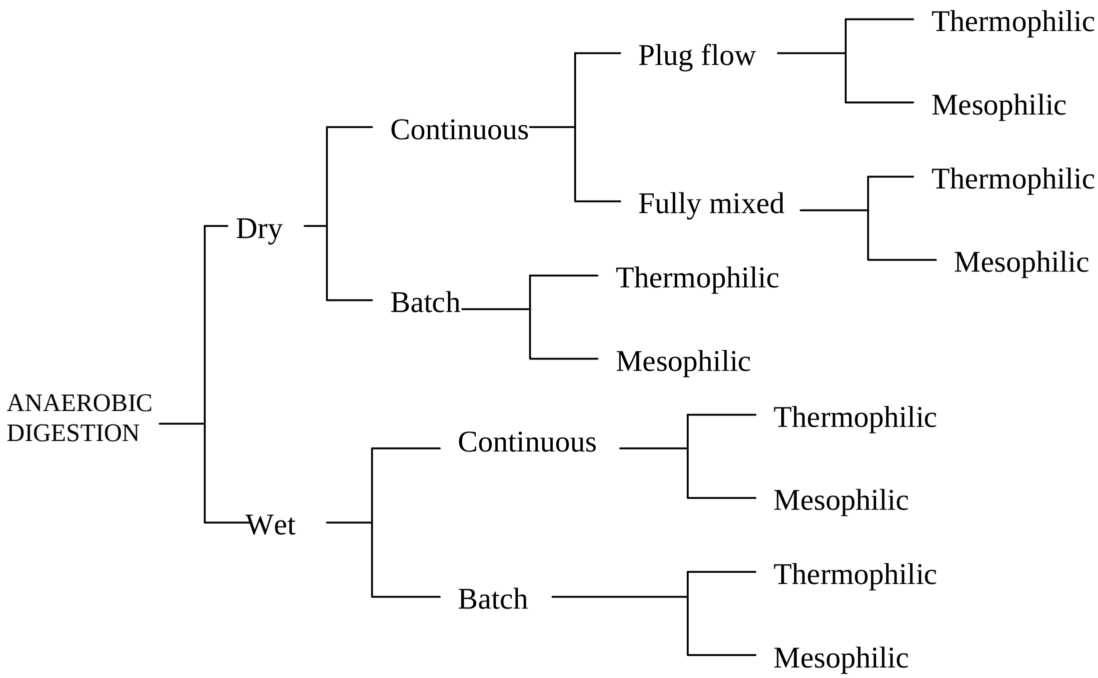


Figure 2.4 Classification of anaerobic digestion by operational criteria (Evans, 2001)

2.8.1 Continuous versus batch process

In a continuous process, the substrate is added to and removed from the digester continuously. Since fresh substrate is added continuously, all reactions involved in biogas generation will occur at a fairly constant rate. This results in a fairly constant biogas production rate. Usually, two digesters are used in the continuous process and the substrates are digested in two stages. The advantage of this process is that the digesters can be used as storage devices.

About 90% of the full scale plants, currently in use in Europe for the anaerobic digestion of sewage sludge and biowaste, rely on continuous one-stage systems. However, a considerable amount of literature has appeared concerning wastes treatment in two phases; first an acid forming phase followed by a methanogenic phase. A likely reason for this discrepancy is that two-and multistage systems afford more possibilities to the researcher to control and investigate the intermediate steps of the digestion process. Industrialists, on the other hand, prefer one-stage systems because of their simpler designs and lower investment costs.

In the batch process the substrate is fed into the digester and then the digester is sealed for the entire period without adding additional substrate until the decomposition process is near completion. Most of the digested substrate is then emptied and the digester is filled with new substrates, and then the digestion process starts again. In a batch process, the production of biogas is non-continuous. Gas production will peak at the middle of the process and will be low at the beginning and at the end of the process. Typically, in order to ensure a more steady supply of biogas, a number of batch digesters with substrates at different stages of anaerobic digestion are operated in parallel.

2.8.2 Mesophilic versus thermophilic digestion

The biodegradation of Hand Sorted Organic Fraction of MSW (HS-OFMSW) in a CSTR-type digesters at 35 ^{o}C resulted a maximum methane yield ranging from 0.39 to 0.43 m^3kg^{-1} VS added without paper and wood and VS reduction ranged from 63 to 69 %. Furthermore, the methane yield of MS-OFMSW ranged from 0.11 to 0.16 m^3/kg^{-1} VS added and VS reduction was found around 30 % due to its high ash value (Gunasselan, V.N., 1997). However, the quantity of biogas produced as a function of the quantity of introduced raw material will be variable according to several factors such as the quality of the organic matter and the environmental parameters.

In the thermophilic high solids anaerobic digestion, higher OLR and methane production rate can be achieved at reduced HRT. Gunaseelan (1997) studied that the methane yield was around 0.2 m^3kg^{-1} VS added. Digestion under thermophilic condition has many advantages such as higher metabolic rates and a high destruction of pathogens and weed seeds. On the other hand, thermophilic treatment has some drawbacks such as less stability compared to mesophilic conditions. Furthermore, the energy requirements of thermophilic systems are higher than those of mesophilic systems. The effect of temperature is particularly important on the hydrolysis step. The hydrolysis rate of cellulose in thermophilic conditions is about 5 - 6 times higher than that observed in mesophilic conditions (Bouallagui et al., 2004). The advantages and disadvantages of operating the anaerobic digestion process in mesophilic and thermophilic ranges are described in Table 2.6. Comparisons between the plants operating in mesophilic and thermophilic digestion systems are represented in Figure 2.5.

Table 2.6 Mesophilic and Thermophilic Anaerobic Digestion

Parameter	**Mesophilic**	**Thermophilic**
Temperature	30 - 40 ^{0} C	50 - 60 ^{0} C
Residence time	15 - 30 days	10 - 20 days
Total solids (wet) (dry)	 10 -15 % 20 - 40%	 10 – 15 % 20 – 40%
Advantages	• More robust and tolerant process than Thermophilic	• Higher gas production • Faster throughput • Process more sensitive to environmental variables
Disadvantages	• Lower gas production rate, • hence larger digestion tanks • Separate sanitization stage	• Needs effective control • Separate sanitization stage

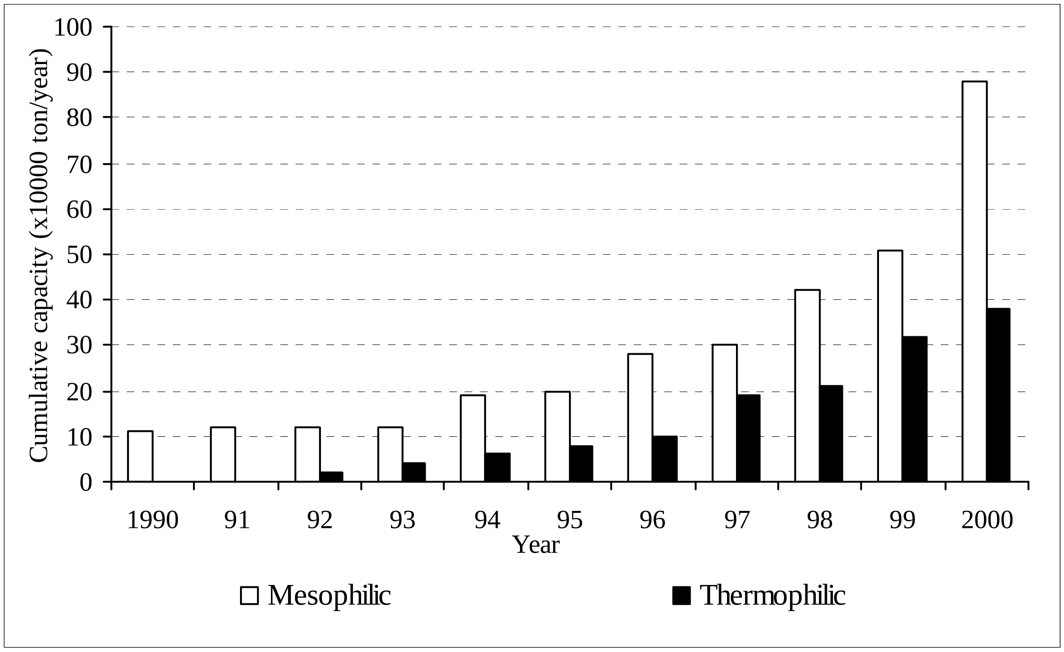


Figure 2.5 Comparisons between Mesophilic and Thermophilic AD Plants in Europe (Verma, 2002)

2.8.3 Single stage versus multi stage digestion

The advance of the High Solid (HS) technology resulted from research undertaken during the 1980's that established higher biogas yield in undiluted wastes. While most of the plants built until the 1980's relied on wet process, the new plants built during the last decade are evenly split between dry and wet systems.

In dry systems, the fermenting mass in the digester has a solid content within a range of 20-40%. The equipment used in this system is robust and expensive than that of Low Solids (LS). Some of the examples of Single Stage High Solid (SSHS) systems are the Dry Anaerobic Composting (DRANCO), Kompogas, and Valorga processes. Due to the viscosity, plug-flow reactors are used. The advantages are that it is technically simple and no mechanical devices need to be installed inside the reactor. Because no mixing occurs within the digester, wastes must be mixed with digestate to provide adequate inoculation. With plug-flow digesters, no short-circuiting can happen as there are no moving parts. Feedstock is added at one end, thus pushing the digestate. The reactor is also smaller because no water is added.

Generally two reactors are used, the first for hydrolysis/liquefaction-acetogenesis and the second for methanogenesis. In the first reactor, the reaction is limited by the rate of hydrolysis of cellulose; the second by the rate of microbial growth. Two-reactor process allows a certain degree of control of the rate of hydrolysis and methanogenesis. For instance, microaerophilic conditions can be used to increase the rate of hydrolysis. The main advantage of the two-stage system is the greater biological stability it affords for very rapidly degradable wastes like fruits and vegetables. The Figure 2.6 depicts the cumulative capacity of anaerobic digestion plants operating in single stage and multi stage systems.

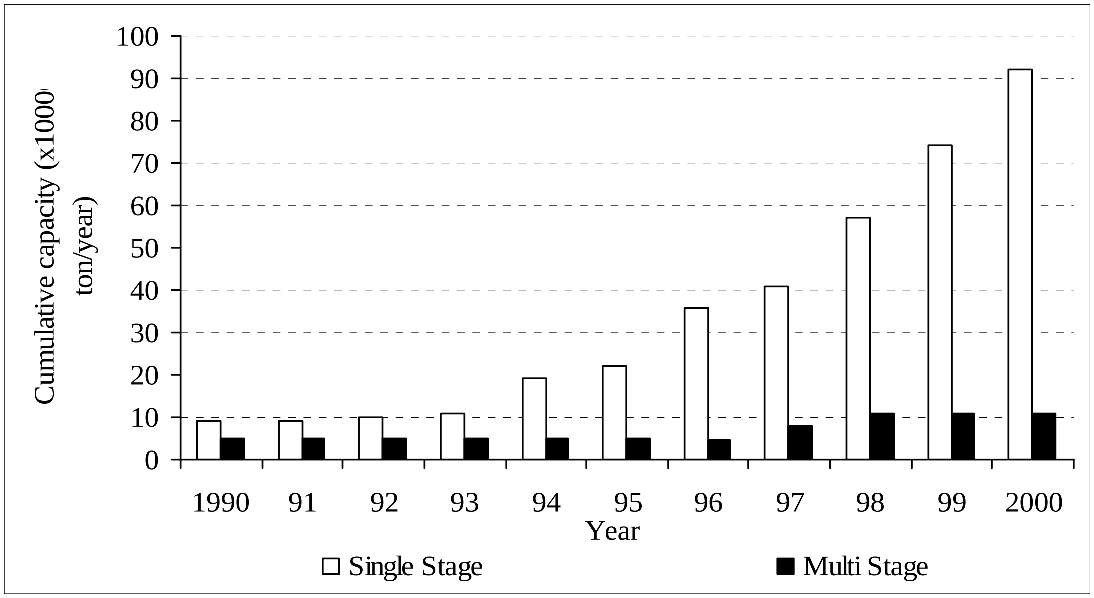


Figure 2.6 Comparison between Single Stage (SS) and Multi Stage (MS) AD plants in Europe (Verma, 2002)

2.9 Factors affecting operation of AD process

The rate at which the microorganisms grow is of vital importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed in the following section.

2.9.1 Waste composition/volatile solids (VS)

The wastes treated by AD may comprise a biodegradable organic fraction, a combustible and an inert fraction. The biodegradable organic fraction includes kitchen scraps, food residue, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. As these lignocellulosic organic materials do not readily degrade under anaerobic conditions, they are better suited for waste-to-energy plants. Finally, the inert fraction contains stones, glass, sand, metal, etc. This fraction ideally should be removed, recycled or used as landfill. The removal of inert fraction prior to digestion is important as otherwise it increases digester volume and wear of equipment.

The volatile solids comprise the Biodegradable Volatile Solids (BVS) fraction and the Refractory Volatile Solids (RVS). Kayhanian and Rich (1995) reported that knowledge of the BVS fraction of MSW helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio. Lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the RVS in organic MSW. Waste characterized by high VS and low non-biodegradable matter is best suited to AD treatment. The composition of wastes affects the yield and biogas quality as well as the compost quality. It is necessary to consider the fact those woody, lignin-rich waste components, e.g., tree and shrub clippings, bark, sawdust and shavings, and straw cannot be fed into the anaerobic process stages in large amounts.

VS are an important parameter for measuring biodegradation, which directly indicates the metabolic status of some of the most delicate microbial groups in the anaerobic system. The VS reduction is measured for the continuous addition of MSW and domestic sewage of high strength effluent. Elango et al. (2007) reported that the initial range of VS reduction is 73% only. After the continuous feeding of substrate, the VS (87%) reduce gradually.

2.9.2 Alkalinity and pH

Sufficient alkalinity is essential for pH control. Alkalinity serves as a buffer that prevents rapid change in pH. The alkalinity is the result of the release of amino groups and production of ammonia as the proteinaeceous wastes are degraded. Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. It has been determined that an optimum pH value for AD lies between 5.5 and 8.5 (RISE-AT, 1998). During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value.

Acidogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Excessive generation of acid can inhibit methanogens, due to their sensitivity to acid conditions. Reduction in pH can be controlled by the addition of lime. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once methane production is stabilized, the pH level stays between 7.2 and 8.2. Ammonium is an important parameter for the buffer capacity in an anaerobic reactor. With concentrations of up to 1000 mg/L, ammonium stabilizes the pH value (Fricke, 2007).

2.9.3 Volatile fatty acids concentration

VFA is important intermediate compounds in the metabolic pathway of methane fermentation and cause microbial stress if present in high concentrations. The intermediates produced during the anaerobic bio-degradation of an organic compound are mainly acetic acid, propionic acid, butyric acid, and valeric acid (Buyukkamaci & Filibeli, 2004). Amongst these, acetic and propionic acids are the major VFAs present during anaerobic bio-degradation and their concentrations provide a useful measure of digester performance. Acetate yield is increased slightly with increasing pH, whereas butyrate yield is increased with decreasing pH. Propionate yield was found to be unrelated to pH (Hu & Yu, 2006). In addition, in municipal wastewater treatment applications, VFA can also be used as an energy and carbon source for microorganisms to enhance the removal of phosphorus and nitrogen. Table 2.7 represents the inhibitory concentration of different parameters in anaerobic digestion system.

2.9.4 Temperature

Due to the strong dependence of temperature on digestion rate, temperature is the most critical parameter to maintain in a desired range. There are two temperature ranges that provide optimum digestion conditions for the production of methane i.e. the mesophilic and thermophilic ranges. The optimum temperature for mesophilic digestion is 35°C and a digester must be maintained between 30°C and 35°C for most favorable functioning. The thermophilic temperature range is between 50°C-65°C (RISE AT, 1998). A thermophilic temperature reduces the required retention time. The microbial growth, digestion capacity and biogas production could be enhanced by thermophilic digestion, since the specific growth rate of thermophilic bacteria is higher than that of mesophilic bacteria (Kim & Speece, 2002b).

Table 2.7 Inhibitors of biomethanization

Parameter	Inhibiting concentration (mg/L)
Volatile acids	>2,000 (as acetic acid) 6,000-8,000 (tolerate)
Ammonia nitrogen	1,500-3,000 (at pH>7.6)
Sulfide (soluble)	>200; >3,000 toxic
Heavy metals	
Copper (Cu)	0.5 (soluble metal)
Cadmium (Cd)	150[a]
Iron (Fe)	1710[a]
Chromium (Cr^{+6})	3
Chromium (Cr^{+6})	500
Nickel	2
Calcium	2,500-4,500; 8,000 (strongly inhibitory)
Magnesium	1,000-1,500; 3,000 (strongly inhibitory)
Potassium	2,500-4,500; 12,000 (strongly inhibitory)
Sodium	3,500-5,500; 8,000 (strongly inhibitory)

Source: Polprasert, 1996

[a] Millimole of metal per kg of dry solids

It has been observed that higher temperatures in the thermophilic range reduce the required retention time. Thermophilic digestion allows higher loading rates and achieves a higher rate of pathogen destruction as well as a higher degradation of the substrate. It is, however, more sensitive to toxins and smaller changes in the environment.

2.9.5 C/N ratio

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Microorganisms need nitrogen for the production of new cell mass. A nutrient ratio of the elements C:N:P:S at 600:15:5:3 is sufficient for methanisation. Optimum C/N ratios in anaerobic digesters should be between 20–30 in order to ensure sufficient nitrogen supply for cell production and the degradation of the carbon present in the wastes (Fricke et al., 2007). As the reduced nitrogen compounds are not eliminated in the process, the C/N ratio in the feed material plays a crucial role.

A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure. Examples of typical C/N values for some materials are shown in Table 2.8.

Table 2.8 Typical C/N ratio for various materials

Raw material	C/N Ratio
Duck Dung	8
Human excreta	8
Chicken Dung	10
Goat Dung	12
Pig Dung	18
Sheep Dung	19
Cow Dung	24
Water Hyacinth	25
Municipal Solid Waste	*40*
Elephant Dung	43
Maize Straw	60
Rice Straw	70
Wheat Straw	90
Saw Dust	>200

Source: RISE-AT, 1998

2.9.6 Retention Time (RT)

The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilc range. The RT is the ratio of the digester volume to the influent substrate flow rate. The Eq. 2.1 gives the time of substrate to be inside the digester.

$$RT = \frac{V}{Q} \qquad \text{Eq. 2.1}$$

Where V = digester volume (m^3)
Q = flow rate (m^3/d)
RT = retention time (d)

2.9.7 Organic Loading Rate (OLR)

Low solids AD systems contain less than 4 - 8 % Total Solids (TS) and High Solids (HS) processes range about 22% or higher TS (Tchobanoglous, 1993). An increase in TS in the reactor results in a corresponding decrease in reactor volume. The OLR is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry. In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading (RISE-AT, 1998). Vandevivere (1999) reported that OLR is twice in HS in comparison to LS. The amount of substrate introduced into the digester is given by Eq. 2.2;

$$OLR = \frac{Q \cdot S}{V} = \frac{S}{HRT} \qquad \text{Eq. 2.2}$$

Where S = substrate concentration ($kg_{substrate}$ in terms of TVS)
OLR = organic loading rate ($kg_{substrate}/m^3_{digester}$)

2.9.8 Solid Retention Time (SRT)

The SRT is the most important factor controlling the conversion of solids to gas. It is also the vital factor in maintaining digester stability. The solids retention time is defined by Eq. 2.3.

$$SRT \quad \frac{(V)(C_d)}{(Q_w)(C_w)} \qquad \text{Eq. 2.3}$$

Where V = digester volume (m^3)
C_d = solids concentration in digester (kg/m^3)
Q_w = volume wasted each day (m^3/d)
C_w = solids concentration of waste (kg/m^3)

In a conventional completely mixed or plug flow digester, the RT equals the SRT. However, in a variety of retained biomass digesters the SRT exceeds the RT. As a result, the retained biomass digesters can be much smaller while achieving the same solids conversion to biogas.

2.9.8 Mixing

The purpose of mixing inside the digester is to homogenize the material. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester. The methane yields under different operational parameters, types of substrate used, and removal of VS are given in Table 2.9.

2.10 Current status of AD treatment processes

Anaerobic digestion is an alternative process to produce energy from solid organic waste. The technology is well proven and realized in many industrial plants all over the world. There are 22 digestion plants in Spain and The total waste capacity for organic fraction of MSW installed in the Spanish plants is approximately 1.4 Mtons (Korz, 2005). The anaerobic digestion is widely-used technology in Europe (Chavez-Vazquez & Bagley, 2002). In Europe, more than 36,000 anaerobic digesters are in operation , treating around 40-50% of the sludges generated (Mata-Alvarez et al., 2000). Many anaerobic treatment plants are in operation throughout the world. Some of them are operating in large scale (>2000 tones/yr) and some are in small scale (<2000 tones/yr) (RISE-AT, 1998). Table 2.10 shows the details of where the plants are situated and what types of feedstock, pretreatment and post treatment are necessary for the respective AD plants. The comparative studies of the AD plants are also described.

Table 2.9 Methane yield from OFMSW

Substrate	**Operational parameters**	**Process**	**Yield (Nm^3/day)**	**CH_4 (%)**	**Degradation (% of VS)**	**References**
SS-OFMSW	5%TS,81-92%VS, 15 days HRT, 2.8 kg VS/m^3.d	T	275-410	62	81	Davidsson et al., 2007
OF-MSW	10% TS, 79% VS,	M	260 L CH4/kg VS	60	61	Nguyen et al. (2007)
MS-OFMSW + PF-OFMSW	20%TS, 62%VS, 13.5 days HRT, 9.2 kg VS/ m^3.d	T	230 $m^3 CH_4$/ton VS	68.7	n.a.	Bolzonella et al., 2003
SS-OFMSW	30%TS, 20-55 days HRT	M	210-290	n.a.	n.a.	Fruteau de Laclos et al., 1997
Manually sorted -OFMSW	18%TS, 90%VS, 19 days HRT, 9.65 kg VS/ m^3.d	T	350	59	65	Gallert and Winter (1997)
MS-OFMSW	88%VS,	T	128-319	n.a.	36-50	Gunaseelan (1997)
MSW only	19 days SRT, 58%VS	M	380 $m^3 CH_4$/ton VS	n.a.	50	Weiland (2000)

SS-OFMSW = Source sorted organic fraction of municipal solid waste
MS-OFMSW = Mechanically sorted organic fraction of municipal solid waste
PF-OFMSW = Putrecible fraction of organic fraction of municipal solid waste
T = Thermophilic
M = Mesophilic
n.a. = no data available

Table 2.10 Comparison of different AD systems

System	Feedstock	Pre-treatment	Process	Post-treatment	Digester volume(m^3)	Capacity (tonnes/yr)	Established
BTA, Helsinger, Denmark	SSHW	- Pulped - Plastic removed - Sanitized for 1 h at 70 ^oC - NaOH added	- Multi stage - Temperature at 38 ^oC		2.4	20,000	1993
Eco-technology, Bottrop, Germany	SSHW	- Organic waste separated from combustible material (RDF) - RDF to fluidized bed boiler	- Single stage -Temp 35^{o}C - Retention time 15-20 days	- Slurry to be pasteurized at 70^{o}C for 30 mins	5	6500	1995
TBW Biocomp process, Thronhofen, Germany	SSMSW	- Fine organic fraction separated from coarse organic fraction - Coarse material to aerobic decomposition by composition - Fine fraction pulped and mixed with liquid from digested sludge	- Two stage reactors - Stage 1(35^{o}C) mesophilic - Stage 2 (55^{o}C) thermophilic - Retention time two weeks in each reactor	- Solid part of sludge mixed with matured compost	100	13,000	1996
Vanaspati Kachara biogas plant, India	PKW	- Waste chopped into small pieces - Few buckets of slurry from active system introduced at start-up	- Continuous		8.25	<200	1989

Garbage gas manure pilot plant, Bardoli, India	KWGSW	- Shredded - Aerobic pre-digestion	- Batch - Retention time 40 days				1989-1991
Rottaler Model, Bavaria, Germany	SSOW	- Hand sorting - chopping	- Multi stage - Stage 1 (37oC) stabilization for 7 days - Stage 2 (55oC) thermophilic for 2-15 days	- Separation tank, liquid pumped from top, solids from bottom of tank	540 (each)	2000	1994
Anyang City, Korea	FW	- Sorting - Shredding	- Multi stage - Stage 1 Acetogenesis - Stage 2 methanogenesis		Stage 1 - 15 Stage 2 – 45	1000	1993
DRANCO process	SSHW	- Manually sorted - Shredded - Magnetic separator - Mixed with water	- Single stage - Thermophilic (50^{o}C-58^{o}C) - Retention time 15-30 days	- Sludge dewatered and stabilized aerobically for 2 weeks		11,000 – 35,000	1992

Source: RISE-AT, 1998

SSHW = Source Separated Household Wastes only
SSMSW = Source Separated Municipal Solid Waste
PKW = Plant and Kitchen Waste
KWGSW = Kitchen Waste and General Solid Waste
SSOW = Source Separated Organic Waste
FW = Food Waste

2.11 Post treatment of residual fraction from AD

After anaerobic digestion, the material usually requires refining before it can be used for fertilizer or soil amendment. If the feedstock is processed wet, the material may be spread directly onto farmland as slurry or it can be separated into a solid and liquid fraction. The solid fraction can be matured for about two to four weeks to provide dry and fully stabilized compost. Either the liquid fraction may be recycled for the dilution of fresh waste, applied directly to farmland as a liquid fertilizer, or sent to a wastewater treatment plant. If the MSW is treated in a dry process, the digested material is usually dewatered and matured to compost. Most of the liquor is recycled to moisten and inoculate the incoming raw MSW, but there will usually be a small surplus that can be spread on farmland as a liquid fertilizer, or treated in a wastewater treatment plant. The amount, quality and nature of digestate depend upon the quality of the feedstock to the anaerobic digestion process, the method of digestion, and the extent of the post-treatment refining process. As the digestate can be used as soil conditioner after post treatment, the energy consumption in fertilizer manufacturing could be reduced (Monnet, 2003). Application of digestate or liquor to farmland is dependent on digestate quality and local regulations.

The ability to utilize the residues of anaerobic digestion as soil amendments improves the economics and environmental benefits of the AD process. Use of this residue depends on its agronomic characteristics and pollution potential which can be assessed on the basis of the following physical, chemical and biological characteristics. The chemical characteristics of digestate are related to the presence of heavy metals and other inorganic contaminants, persistence organic contaminants and nutrients like Nitrogen, Phosphorus and Potash (NPK).

According to their origin, organic waste can contain hazardous matters, which can result in new routes of transmission of pathogens and diseases between animals, humans and environment. Thus quality control of this type of biomass is essential in relation to the biological treatment i.e. pathogens.

The presence of impurities in the digestate can cause a negative public perception of the AD technology, aesthetic damage to environment, increase the operational costs. The physical impurities that can be in the digestate are plastic and rubber, metal, glass and ceramics, sad and stones, cellulosic materials.

The contamination of the digestate inevitably depends upon the nature of the feedstock, the pretreatment applied and digestion itself. For the digestion of MSW, source segregation is more efficient than mixed collection because the mechanical pre-treatments are not as effective in removing contaminants as is the elimination of potential contaminants at source.

a. Dewatering of digestate

After completing the anaerobic digestion process, the digestate is commonly subjected to post treatment. Such treatment involves dewatering, aeration and leachate treatment. The digestate usually contains fiber and liquor which has to be separated. There are different methods of dewatering such as screw press, wire presses, centrifuges, decanters and cyclones. The filtered cake is cured aerobically, usually in compost piles, to make compost. The fiber is bulky and contains a low level of plant nutrients so it can be used as soil conditioner.

The liquor contains a large proportion of nutrients and can be used as a fertilizer. Its high moisture content facilitates it application through conventional irrigation methods. However consideration has to be given to application time so that nitrogen, which is more readily available after digestion, is taken up by the crop and not leached into the soil and subsequently groundwater.

b. Composting of digestate

In order to obtain a high quality product, with a higher value, the digestate can be processed into compost. It would ensure a complete breakdown of the organic components as well as fixing the mineral nitrogen onto humus like fraction, which would reduce nitrogen loss. As an additive to composting process, it provides a good source of nitrogen for seeding up the process. At the same time, it enriches the compost in phosphorus and micro nutrients such as manganese (Mg), iron (Fe) etc. the water content of the digestate is also interesting for maintaining the moisture in the composting process. The compost made from MSW has to meet consumer and market requirements. The following criteria are important to ensure the marketability:

- It must be largely free of impurities
- It must not present any health hazards
- The level of heavy metals and other toxic substances must comply with the standards
- The product must have a visually attractive overall impression.

2.12 Co-digestion of OFMSW

Several characteristics make AD of the organic fraction of MSW difficult. In many cases it may be an advantage (economical and regarding energy production) to co-digest the waste with another waste stream. The use of a co-substrate in most cases improves the biogas yields due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates. In addition, economic advantages derived from the fact of sharing equipment are quite significant. 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 and the use of common access facilities. The organic fraction of the MSW is mixed with animal manure and the two fractions are co-digested. This improves the carbon/nitrogen ratio and improves gas production. As OFMSW and sewage sludge are producing in large quantities in many places, much research has focused on this particular issue.

Chapter 3

Methodology

3.1 Introduction

In this study, the organic fraction of AIT solid wastes was segregated for biological treatment by anaerobic digestion process as a part of solid waste management strategies. The research was conducted on pilot scale digester to study the effects of operational parameters especially organic loading rates, retention time on stability of AD process. The wastes for the feedstock were collected from AIT. After collecting the wastes, the manual separation of the readily degradable organic fractions was carried out from the waste stream. The segregated wastes were fed into the shredder to obtain the average particle size of 10 mm. The inoculums were blended to the shredded small sized waste particles to enhance the start-up of the digestion process. To control the pathogens and reduce the digestion period the experiment was carried out at thermophilic condition of 55 ^{o}C. The details of research methodology are described in Figure 3.1.

Dewatering of the digestate was performed using sludge drying bed to facilitate for the further use of the digestate and the nutrient contents of the digestate were also analyzed to determine the suitability of the digestate for fertilizer. Moreover, the energy balance and mass balance of volatile solids were also conducted.

3.2 Pilot scale continuous digestion system

3.2.1 Design of the digester

The digester was designed according to the organic loading rate and the hydraulic retention time. A single stage anaerobic digestion was operated at different organic loading rates to optimize the biogas production and to investigate operational parameters. The digester was cylindrical with double wall container to provide hot water bath in order to maintain the temperature inside the digester. For facilitating digestate disposal the digester was inclined at 30 degree and was also accommodated with piped outlet at bottom in order to prevent the intrusion of air inside the reactor during withdrawal. The digestate from the digester was collected into the digestate collection container with progress cavity pump and part of it was recirculated.

The total volume of the digester was approximately 690 L with working volume of 552 L and the inside diameter of the cylindrical digester was 600 mm. The digester was also accommodated with other accessories such as heater for maintaining temperature of water bath and wet gas meter to measure the biogas production. For the post treatment of the digestate, rectangular sand drying bed of size 75 cm radius and 80 cm high was used. The leachate had been collected through drain pipe as shown in Figure3.2. The Figure 3.2 shows the detail design of pilot scale DCAD system along with the supporting equipments such as heater, pump, wet gas meter, thermometer, and pipe lines.

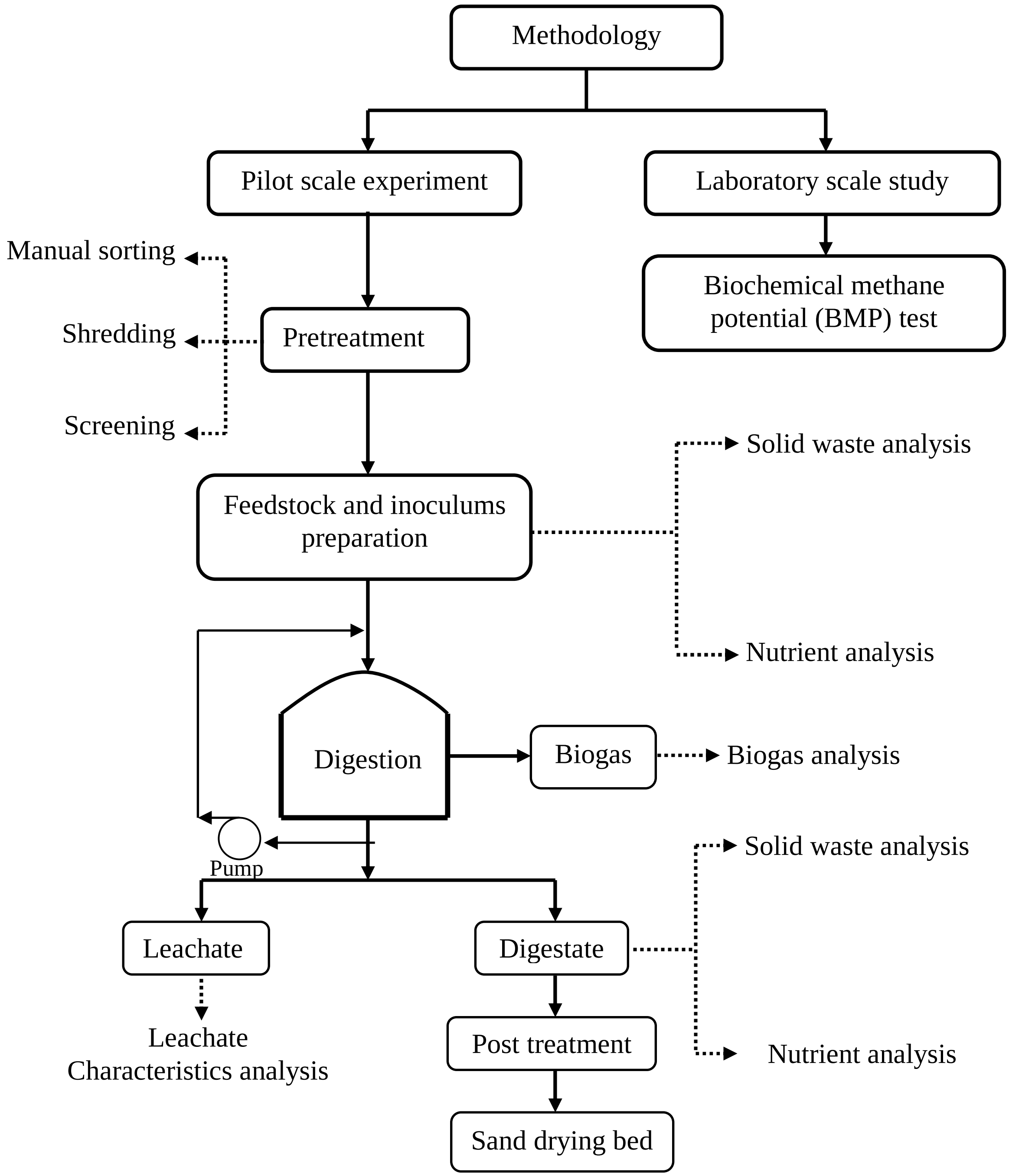


Figure 3.1 Diagram of research methodology

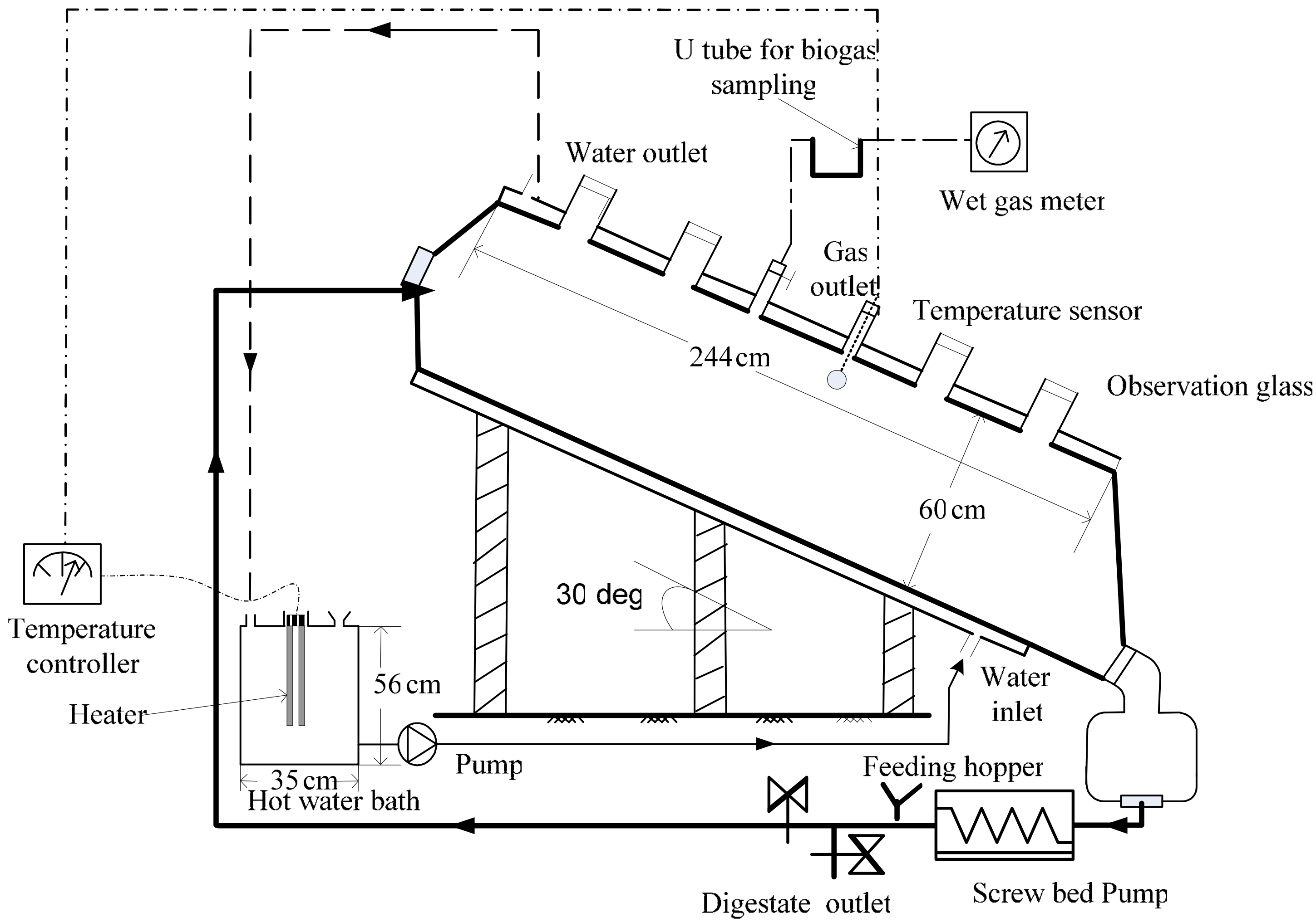


Figure 3.2 Detail design of pilot scale dry continuous anaerobic digestion system

3.2.2 Experimental procedure

a. Feedstock composition

The solid wastes from AIT transfer station were used as substrate for the AD system. The compositions of which were determined by solid wastes analysis techniques. Accordingly the representative wastes were collected and the weights of wastes were reduced to sample size of 100-200 kg by coning and quartering technique. The feedstock was comprises of food wastes.

b. Feedstock preparation

After manual sorting of the wastes material it was converted into averages size of about 10 mm by using shredder. The surface area is more at the smaller size and the hydrolysis process occurs faster which is the limiting factor of the methane formation in anaerobic digestion. Fresh wastes were mixed with the inoculums to enhance the start-up process and were fed into the digester based upon the organic loading rate. To maintain the optimum C/N ratio of 20-30 range inside the digester the feedstock was blended with food wastes, fruit wastes and boiled rice to appropriate proportion.

c. Inoculums

Inoculum source is a very important operational parameter. Also, it is crucial the selection of waste/inoculum ratio as well as the assessment of anaerobic biodegradability of solid wastes. The percentage of inoculation for acidogenic fermentation of organic urban wastes is approximately 30% (w/w) (Carreiro et al., 2006). Cow dung, digestate material, anaerobic sludge was used as inoculums components. The inoculums were prepared as per previous researchers; Lien (2004), Juanga (2005), Adhikari (2006) and Eliyan (2007) with some modification. The constituent of inoculums was cow dung, anaerobic sludge and digestate material in the ratio of 2:1:1. The purpose of using these mixtures was to increase the microbial diversity inside the reactor.

d. Mass balance

The feedstock to the system was consisting of solid phase and liquid phase as the food wastes generally had high moisture content of about 70-80. Since the system was operated under high solid AD system, the percentage of TS was above 15%. The output of the system was biogas, the volume and mass of which was determined as described in Eq. 3.1. The material balance occurring in the AD process is explained in Figure 3.3.

Biogas produced contained methane, carbon dioxide, water vapor and trace amount of other gases. Trace amount of other gases were neglected for volumetric calculation of the biogas in this study. Molecular weight of methane (16 g/mol) and carbon dioxide (44 g/mol) were used for evaluating the biogas mass. The molar volume of ideal gas at STP is 22.413 L/mol and normalized gas contents are estimated as:

$$G_m = V \times [(16 \times CH_4/100) + (44 \times CO_2/100)]/22.413 \qquad \text{Eq.3.1}$$

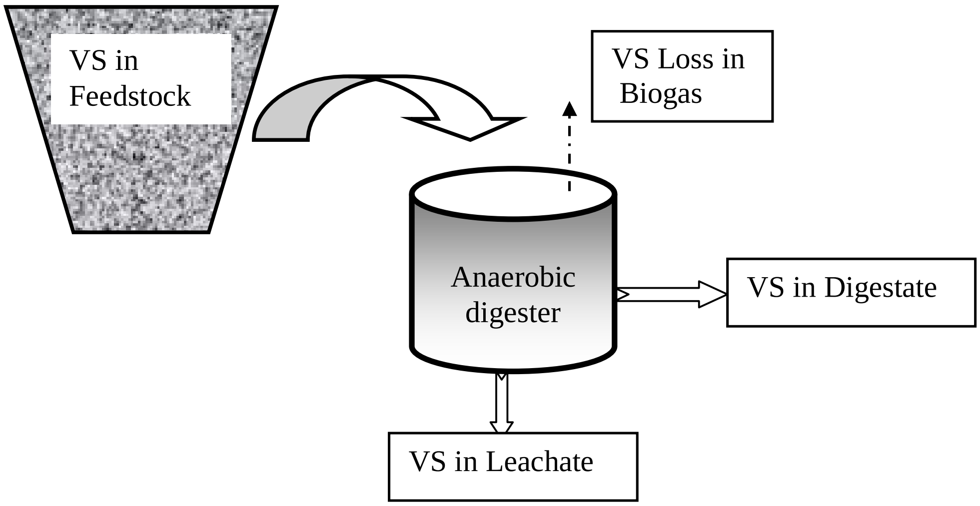


Figure 3.3 Material balance analyses in AD process

Where, G_m = mass of biogas, (g)
V = biogas volume at STP, (L)
CH_4 = normalized methane content (vol %)
CO_2 = normalized carbon dioxide content (vol %)

- **Feedstock intake**

As the moisture content in organic fraction of municipal solid waste was very high, the feedstock was comprise of solid and liquid phase. The amount of solid and liquid entering into the system was determined by using Eq. 3.2.

Total feedstock bulk weight (kg) = X
Moisture content (%) = w
Volatile solid (%) = Z
Total moisture in a give weight of waste (kg) = w x X
Total dry solid present in the waste (kg) = (1-w) x X

$$\text{Total feedstock intake } (X) = (w \times X) + [(1-w) \times X] \qquad \text{Eq. 3.2}$$

- **Digestate withdrawal**

The output of the AD process was in the form of digestate and leachate. The quantity of digestate going out of the system was determined as follow:

Total bulk digestate withdrawn (kg) = Y
Moisture content of digestate = w1
Total Moisture content = w1 x Y
Solid in leachate (g/L) = SL
Total dry solid in digestate (kg) = (1-w1) x Y
Volatile solid in digestate (%) = Z_1

- **Water balance**

Moisture content of the feedstock was converted into the leachate and partly associated in digestate. To extract the moisture content of digestate, the digestate was dried in sand drying bed. The Eq. 3.3 depicts the quantity of leachate produced from the AD system.

$$\text{Total liquid in} = \text{Total liquid out}$$
$$(w \times X) = (w_1 \times Y) + \text{Leachate } (L)$$

So the total leachate withdrawal $(L) = (w \times X) - (w_1 \times Y)$ Eq. 3.3

- **Volatile solid balance**

Organic fraction of solid waste consists of high volatile matter which has high potential to produce biogas. Volatile solid in leachate can be calculated as L x VS_L. The reduction of volatile matter during digestion indicates the system performance. Therefore, evaluation of volatile matter in the system is important. The part of volatile matter is converted into biogas and remaining goes to digestate along with leachate. The balance of volatile matter is described in Eq. 3.4 and Eq. 3.5 represents the quantity of digestate to be withdrawn.

Volatile solid in = volatile solid out

$$(1-w) \times X \times Z = [(1-w_1) \times Y \times Z_1] + \{V \times [(16 \times CH_4/100) + (44 \times CO_2/100)]/22.413\} + L \times VS_L \qquad \text{Eq. 3.4}$$

Total digestate to be withdrawn (kg) $Y = \dfrac{(1-w) \times X \times Z - L \times VSL - Gm}{(1-w_1) \times Z_1}$ Eq. 3.5

e. Digester operation procedure

The feedstock was seeded with inoculums to start-up the digester. The inoculums were fed about 30 % of the total waste volume. The pH of the digester was adjusted by adding commercial soda (NaOH) until the stabilization of AD process was occurred. The experiment was conducted in one reactor i.e. single stage high solid anaerobic digestion process. The complete start-up of the digester was checked from the stability of the gas production and volatile fatty acid formation. After the complete acclimatization of the reaction the fresh waste was fed continuously according to the loading rates explained in Table 3.1. The digestate was withdrawn as determined by Eq. 3.5 and 8 parts of the withdrawal digestate was recirculated into the digester by progressive cavity pump. The purpose of recirculating the digestate was to enhance the mixing and homogenization of the fresh wastes inside the digester. Biogas produced was monitored daily. The inhibiting substances such as VFA and ammonia nitrogen were also measured daily.

Table 3.1 Pilot scale experimental reactor runs

Phase 1: Reactor starts up			
Particle size = 10 mm Wet waste weight = 386 kg Inoculums addition= 30% of substrate, consists of cow dung, anaerobic sludge, and digested waste in the ratio of 2:1:1 Temperature in mesophilic range and was increased 2^{o}C per day to thermophilic condition (55^{o}C) Note: pH was adjusted until pH of the leachate is near about 7			
Phase 2: Continuous feeding			
Loading	Constant	Variables	Remarks
Loading 1	Particle size = 10 mm Feeding and withdrawing mode of operation through material balance analysis Temperature = Thermophilic condition (55^{o}C) Mass retention time:25 days	Loading 2.5 kg VS/m^{3}day Wet waste = 9 kg/day	TS = 18.69 % VS = 84.07 %
Loading 2	Particle size = 10 mm Feeding and withdrawing mode of operation through material balance analysis Temperature = Thermophilic condition (55^{o}C) Mass retention time:25 days	Loading 3.3 kg VS/m^{3}day Wet waste = 13.5 kg/day	TS = 17.38 % VS = 77.86 %
Loading 3	Particle size = 10 mm Feeding and withdrawing mode of operation through material balance analysis Temperature = Thermophilic condition (55^{o}C) Mass retention time:25 days	Loading 3.9 kg VS/m^{3}day Wet waste = 12 kg/day	TS = 21.68 % VS = 83.17 %

To achieve the OLR of 2.5 kg VS/m^{3}.d and maintain C/N ratio of 20.1, the food waste was blended with food wastes, fruit waste and boiled rice in the ratio of 13.6:5.4:1. Similarly, other loading rates were maintained with the heterogeneous characteristics of the wastes.

3.3 Determination of methane potential of organic wastes

To compare the performance of the digestion system, the methane potential of the AIT solid wastes was determined in the laboratory scale. For analyzing the methane potential of wastes, BMP test procedure was followed. The basic approach is to incubate a small amount of the waste with anaerobic inoculums and measure the methane generation, usually by simultaneous measurements of gas volume and gas composition.

3.3.1 Procedures for measuring methane potential

The method was used to characterize organic waste, separated from AIT solid waste, regarding methane potential as relevant in the context of treatment by anaerobic digestion.

The main goal was to determine the methane potential of solid wastes per gram of organic waste expressed as VS. The result was converted into Standard Temperature and Pressure (STP) condition. The methane generation as a function of time may also be of interest for identification of inhibition. These priorities had promoted a procedure including extensive homogenization of the solid waste sample, large inoculums, incubation at 55 ^{o}C for 50 days, and direct measurement by a Gas Chromatograph (GC) of CH_4- mass produced.

In the laboratory, the waste sample was first blended in a blender to reduce particle size and mix the sample. The mixing was done without addition of water. A large sub-sample of about 1–2 kg was taken to determine the dry matter content of the original sample. After homogenization, the sample was mixed with active anaerobic inoculums. The test was carried out as triplicate batch experiments. Triplicates were used because the method was a biological test method using inoculums from previous digestate (varying quality) and the test material (waste) was relatively heterogeneous. The sequential procedural of conducting BMP test is described in Figure 3.4.

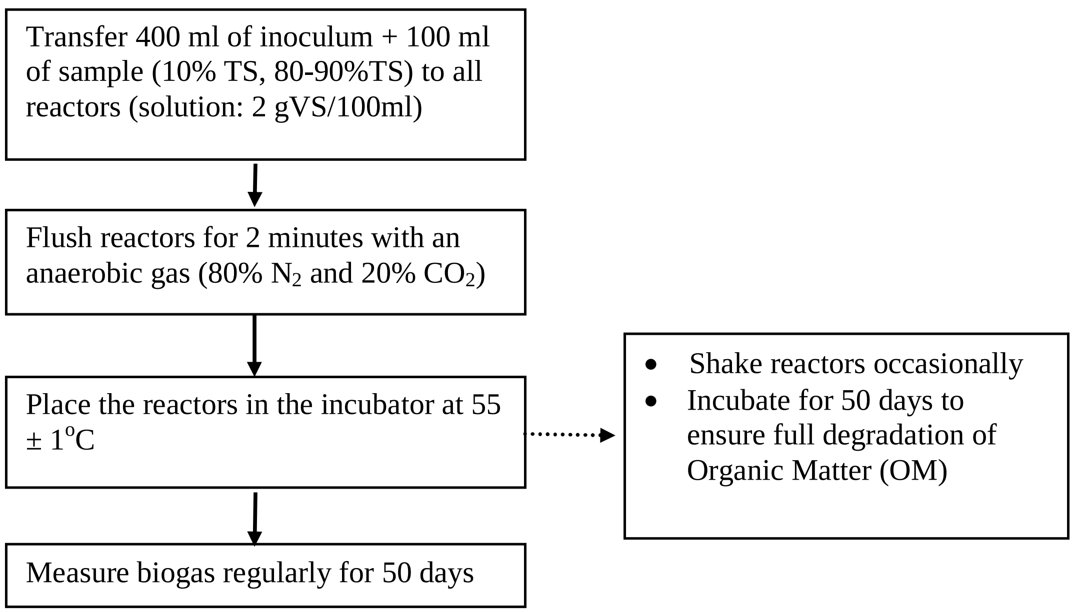


Figure 3.4 The detail procedure of BMP test (Hansen et al., 2004)

3.3.2 Equipment and supplies for BMP test

The following equipment and supplies were used:

- Two-liter glass bottles with a thick rubber septum were used as reactors.
- Pulverizer was used to make the feedstock to the size of about 2 mm.
- Inoculum from previous digestate, cow dung, sewage sludge.
- An incubator at 55 ^{o}C for the incubation.
- 1 ml glass syringes with pressure lock to allow sampling of a fixed volume at actual pressure from the reactors.
- Gas chromatograph
- Gas mixture of 80% N_2 and 20% CO_2 (alternatively, N_2-gas can be used)

3.3.3 Important of BMP test

Use of pressure tight syringes and direct measurements of methane on a GC reduce the workload. The above mentioned procedure is simple and has the potential of being commonly used, both for measurement of methane potentials and for studies on enhancement and inhibition of methane potentials.

3.4 Sampling and analytical procedure

It is recognized that selecting a representative sample is one of the most difficult tasks associated with a waste stream analysis. It is of critical importance that a sample to be collected should be representative. The representative samples from AIT were collected and were reduced to manageable size as the actual classification of materials were carried out by hand. The sample size for characterization was between 100 - 200 kg and the size reduction was achieved by a coning and quartering technique.

The analysis in this study was made for feedstock, digestate, leachate and biogas produced. The parameters to be analyzed for feedstock and digestate were Moisture Content (MC), TS, and VS. These parameters were used to compare the system performances and were controlled to provide the stability of the system. All analytical determinations were performed according to "Standard Methods"(APHA, AWWA and WEF, 1998). In addition to above mentioned operational parameters, nutrients (nitrogen, phosphorus, potassium, carbon) in the fresh wastes, digestate and leachate were also analyzed.

3.4.1 Solid waste analysis

Both fresh waste and digested waste were subjected to solid analysis. Solid waste analysis was conducted before feeding into the digester and after withdrawing the digestate from digester. Representative grab sample of Solid waste were collected and were analyzed for parameters such as moisture content, TS, VS and bulk density.

- **Moisture content determination**

The percent moisture of the MSW samples was determined by weighing 100 g of the samples into a pre-weighed dish and drying the samples in an oven at 105 ^{o}C for 24 hours to a constant weight. The percent MC and TS were calculated using Eq. 3.6 and 3.7. The analysis was conducted in duplicates. After determining the moisture content, the samples were further tested for volatile matter content as explained in the section that follows.

$$\% MC = [(Wet\ Weight - Dry\ Weight)/\ Wet\ Weight] \times 100\% \qquad \text{Eq. 3.6}$$

$$\%TS = 100\% - \%MC \qquad \text{Eq. 3.7}$$

- **Volatile solid determination**

The volatile solid content was determined by the method of ignition of the sample at 550 °C for 1 hour. The same sample as was determined for moisture content and total solid was used for determining volatile solids. The dried samples were pulverized into fine solids and were mixed properly to ensure homogeneity. After that the pulverized sample were weighed for 2 grams and were placed on several evaporating dishes. Then the sample was evaporated for at least 1 hour at 550 ^oC in the muffle furnace. After drying the sample was placed into desiccator for cooling and was weighed immediately by using analytical balance. Thus volatile solid was calculated using Eq. 3.8.

$$\% VS = \frac{w_0 - w_f}{w_0 - w_e} x100\% \qquad \text{Eq.3.8}$$

Where w_0 = weight of sample and evaporating dish after 105 ^oC
w_f = weight of sample and evaporating dish after 550 ^oC
w_e = weight of empty dish

- **Total solids and Volatile solids loss determination**

The mass balance of the digester is presented on Figure 3.5. The feedstock entering into the digester for AD process has an initial total wet weight of TW_0 and dry mater M_0. The residue for the overall process has the final total weight of TW_1 and dry matter M_1.Total solid loss can be determined by using Eq. 3.9. The Eq. 3.10 gives the dry weight of material before feeding into the digester whereas Eq. 3.11 depicts the dry weight of digestate. For calculating the loss of volatile solid, Eq. 3.12 can be used similarly Eq. 3.13 and 3.14 represents the amount of volatile solids in the feedstock and digestate respectively.

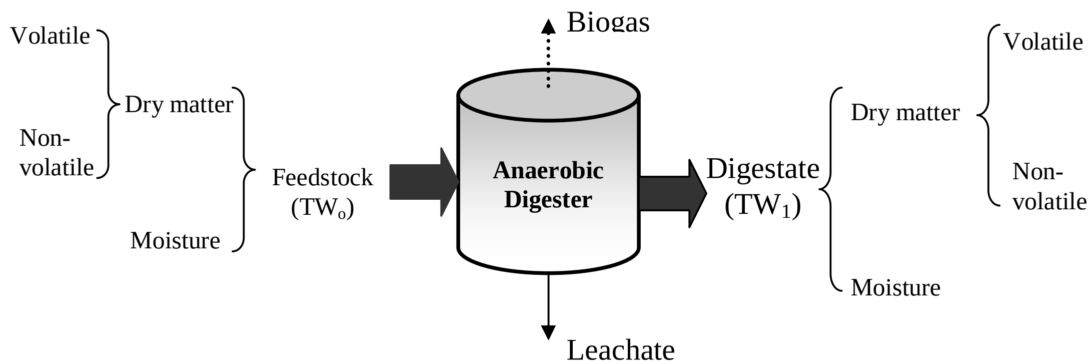


Figure 3.5 Material balance of anaerobic digestion system

The following equations were used to obtain percentage of total solid (%TS) loss and percentage of volatile solids (%VS) loss.

$$\% TS = \frac{M_0 - M_1}{M_0} x\ 100\% \qquad \text{Eq. 3.9}$$

Where M_0 = dry weight of feedstock entering into the reactor, (g)

$$M_0 = TW_0 \ x\ TS_0 \qquad \text{Eq. 3.10}$$

TW_0: wet weight of solid wastes entering into the reactor, (g)
TS_0: percentage total solid of feedstock (%TS)
M_1: dry weight of digestate extracting from reactor, (g)

$$M_1 = TW_1 \times TS_1 \qquad \text{Eq. 3.11}$$

TW_1: wet weight of digestate extracting from the reactor, (g)
TS_1: percentage total solid of digestate (%TS)

$$\% \, VS = \frac{N_0 - N_1}{N_0} \times 100\% \qquad \text{Eq. 3.12}$$

Where N_0 = weight of volatile solids entering into the reactor, (g)

$$N_0 = M_0 \times VS_0 \qquad \text{Eq. 3.13}$$

VS_0: percentage volatile solid of feedstock (%TS)

N_1: weight of volatile solid of digestate extracting from reactor, (g)

$$N_1 = M_1 \times VS_1 \qquad \text{Eq. 3.14}$$

VS_1: percentage volatile solid of digestate (%TS)

3.4.2 Nutrient analysis

The nitrogen and phosphorus contained in the MSW are sufficient to satisfy the cell growth requirements during biogas production (Elango et al, 2007). The others elements, such as sodium, potassium, calcium, magnesium and iron are present in low concentrations. However, they may exhibit inhibitory effects at higher concentrations. Nutrient concentrations vary in most organic wastes. So its analysis is essential to provide proper environmental conditions for microbes inside the reactor. Both fresh wastes and digestate were analyzed for nitrogen (N), phosphorus (P), and potash (K) as they are major nutrient constituents in MSW. Table 3.2 shows the methods of analyzing nutrients.

Table 3.2 General information on nutrient analysis

Parameters	Method/Instruments	Detection limits (mg/L)
Nitrogen (%)	Macro-Kjeldahl analysis	-
Phosphorus (%)	ICP-AES	0.02
Potassium (%)	ICP-AES	0.01

3.4.3 Biogas analysis

To measure the performance of AD process, the biogas produced was monitored daily on-line with a wet gas meter (Ritter TG 05, Germany). Gas samples (0.2 ml) were taken from the headspace of the reactors through the septum with a syringe with pressure lock (see Fig 3.5). The pressure lock was closed after the needle of the syringe was penetrated the septum and was inside the reactor headspace, making it possible to sample a fixed volume of gas at the actual pressure in the reactor. The syringe was rewithdrawn and the sample was injected directly into the Gas Chromatograph (SHIMADU-GC14A, Japan) equipped with thermal conductivity detector for analyzing volumetric composition of biogas (CH_4, CO_2, H_2, O_2, N_2). From the fixed volume sampled and the measured mass of methane in the sample, the methane content in the reactor headspace can be calculated without measuring the actual pressure in the bottle. Ambient temperature and pressure were measured and Eq. 3.15 was used to determine volume of the gas at STP.

$$Vstp = Vm \frac{Ts.\ Pm}{T_s.P_s} \qquad \text{Eq. 3.15}$$

Where P_m = Ambient pressure (measured)
T_m = Ambient temperature (K)
V_m = Volume of gas measured at ambient condition
T_s = standard temperature (0 ^oC = 273 K)
P_s = standard pressure (1013.25 mb)

Since measurement was carried out in wet condition i.e. saturated with water vapor, dry volume of gas was determined using the Eq. 3.16.

$$Dry\ volume = \frac{P_b\ (Volume\ of\ gas\ sample)}{P_b - P_v} \qquad \text{Eq.3.16}$$

Where P_b = Barometric pressure
P_v = Vapor pressure at ambient temperature

3.4.4 Leachate characteristics analysis

To measure the performance of small scale sand drying bed, leachate from it was analyzed for total Dissolved Organic Carbon (DOC) and COD, dissolved nitrogenous compounds: NH_4-N, TKN, and TS. Table 3.3 describes detail procedure for leachate characteristics analysis:

3.5 Post- treatment of digestate

Sand drying bed found early application with wastewater to dewater sludge, but with the wide scale implementation of mechanical units, their use declined. SDB are usually used for small industrial or community waste treatment plants. The digested sludge can be dewatered on open or cover sand beds. SDB is less complex, easier to operate and requires less operational energy than mechanical dewatering systems. It easily produces a sludge cake with 25-40 percent solids and can exceed 60% with additional drying time.

The SDB was designed to cope with the digestate produced from the AD process. The detail design and construction of the SDB using plastic container are as shown in Figure 3.6 and 3.7. The unit consisted of a 15 cm thick layer of sand over 30 cm of graded gravel. A perforated central pipe collected the filtrate that percolated through the sand and gravel. Sludge that remained on top of the sand bed was solidified by the percolation of water downward into the sand and also from the evaporation from the surface of the sludge.

Sand drying bed design parameters:

1. To facilitate the draining of leachate, 1 inch (2.5 cm) PVC pipe was placed at the center of the container along with screening net and the slope to the pipe was (12/75*100) 16 percent.

2. From bottom to top, the first layer was course gravel of 15 cm in depth, followed by medium and fine gravel of 15 cm in depth.

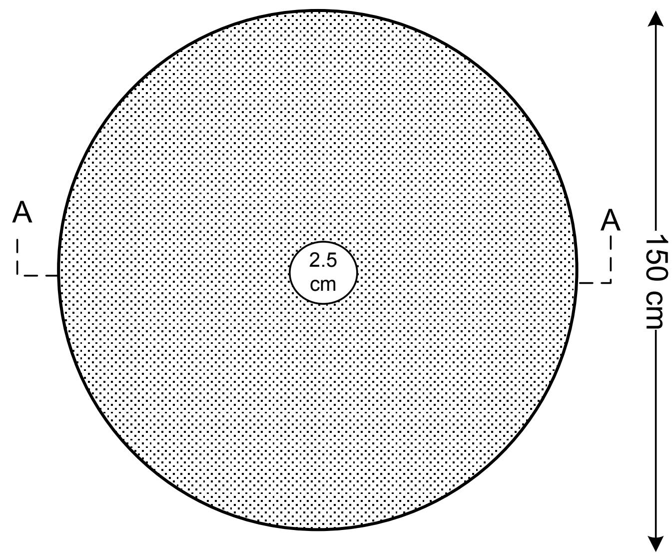


Figure 3.6 Sludge drying bed: Plan view

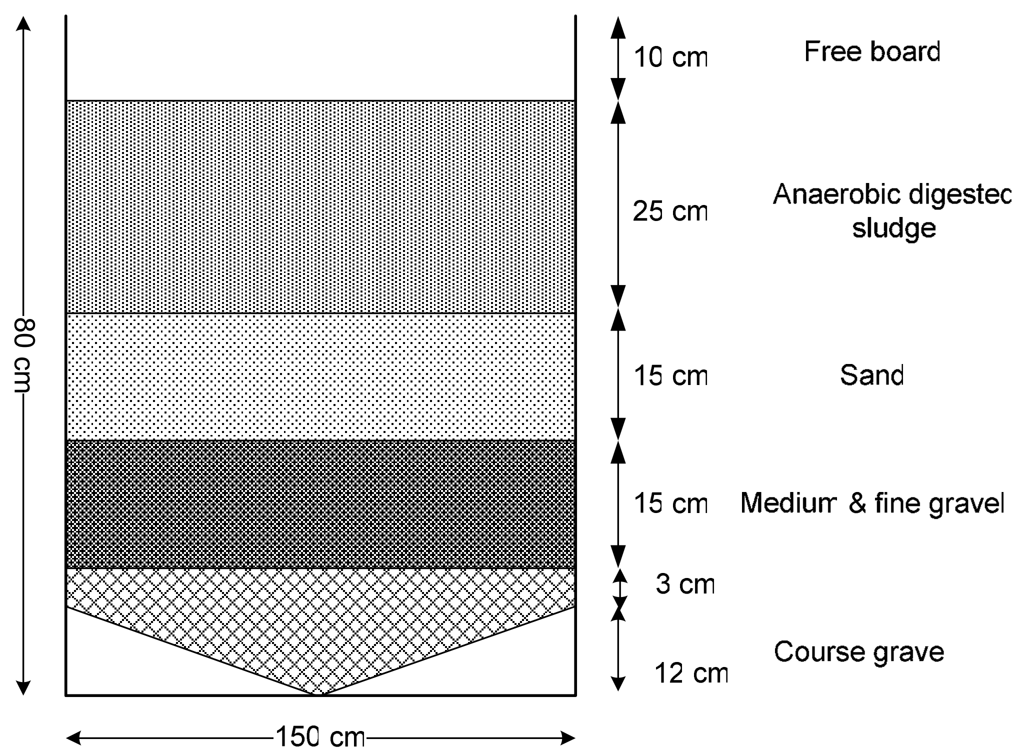


Figure 3.7 Sludge drying bed: Cross-sectional A-A view

3. Last layer was and of 15 cm in depth.

4. The depth of the container allowed approximately 25 cm for anaerobic digested sludge and 10 cm for freeboard.
5. Approximate dying period (retention time) of 10-15 days was allowed under favorable conditions achieving approximately moisture content of 50 percent.
6. The dewatered sludge was a course, cracked surface and dark brown in color.
7. The dewatered sludge removal was accomplished with showel and used for further analysis.

3.6 Energy balance of the process

The energy consumption in the overall AD system was on shredding solid wastes, pumping the digestate to the front end of the reactor and maintaining the constant temperature inside the reactor. Whereas the energy production was from the biogas produced especially methane content. This section describes the economic feasibility of the AD system. The following Eq. 3.17, 3.18 and 3.19 give the energy required for feeding, heating and net energy produced from the AD system respectively. The calorific values of the substrate as well as that of digestate were also considered for balancing the energy during anaerobic digestion process.

- **Mechanical energy requirements**

Energy required for shredding (E_S) $= \dfrac{0.5 \text{ L (gasoline)}}{100 \text{ kg (feedstock)}} * W$

Where W = weight of feedstock (kg)

Since, 1 gallon of gasoline = 110,250 BTU
= 110,250 BTU * 1.0551 [1.0551: conversion factor]
= 116,324.8 KJ/gal

Energy required for feeding (E_F) = P * T Eq. 3.17

Where P = the engine power (kW)
T = Duration of operation (h)

- **Calorific energy requirements**

The calorific energy is the energy required to heat influent substrate and to maintain digester temperature. The daily calorific energy requirement E_H (KJ/d) necessary to increase the substrate temperature from it's stocking value T_o (^oC) to the temperature of the digester T_i(^oC) is given by Eq. 3.17;

$$E_H = Q * C_p * \rho (T_i - T_o) \quad \text{Eq. 3.18}$$

Where Q = substrate flow rate (m^3/d) mass of water (L)
C_P = specific heat of feed (kJ/kg ^oC)

- **Energy production**

The daily energy production in an anaerobic digester E_A(KJ/d) corresponding to that of methane contained in the produced biogas is given by Eq. 3.18;

$E_A = (M_P) * (\text{L.H.V. of methane})$ Eq. 3.19

Where M_P = daily methane production rate (L CH_4/d)
L.H.V. = 35.8 KJ/L CH_4 (Bouallagui et al., 2004)

- **Net energy production**

The net energy production EP (kJ/d) is the difference between the produced energy and the energy consumed by the process:

$$\mathbf{E_P = E_A - E_S - E_F - E_H}$$

Table 3.3 Leachate characteristics analysis

Parameter (unit)	Method/ Instruments	Preservation & Recommended max. storage	Applicable range and accuracy	Interferences
DOC (mg/L)	High temperature combustion method(SHIMADZU TOC-V_{CSN} Non-dispersive infrared analyzer detector with standard TC catalyst)	Refrigeration (4 ^oC), 7days	>20 ppm 5-10%	Inorganic carbon
COD (mg/L)	Standard method 5220C: Closed reflux titration method	Refrigeration (4 ^oC), 7days	>50 mg/L, not applicable if Cl^-> 2000 mg/L	Halides ions like Chloride Nitrite (NO_2^-)
NH_4-N	Standard method 4500B: Distillation method	-	-	-
TKN	Standard method 4500B: Macro kjeldahl method	Refrigeration, 24 hours	<5 mg/L	Nitrate>10 mg/L, Inorganic salt and solids
pH	pH meter electrode	Immediate analysis	(1-14) ± 0.1	Sodium if pH>10 and temperature
Alkalinity (mg/L as $CaCO_3$)	Titration method	Refrigeration (4^oC), 24 hours	Standard deviation; 5 mg/L	Soap, oily matter, suspended solids
VFA (mg/L)	Gas chromatograph (SHIMADU-GC14 A with TCD detector)	Immediate analysis	95% accuracy	Presence of synthetic materials like detergents

Chapter 4

Results and Discussions

This section describes the results obtained during the pilot scale anaerobic digestion of MSW operating in thermophilic condition. The characteristics of the wastes stream are presented. The experiments were conducted in two phases i.e. start-up and continuous loading. The results of the BMP test are also illustrated to compare the performance of the system in terms of biogas production and volatile solids reduction. The experiments were conducted with three different continuous loadings for constant retention time. The analyses and evaluation are described to examine the performance of several strategies particularly in pilot scale experiment to achieve the objectives of this study.

4.1 Waste segregation in AIT

The Asian Institute of Technology (AIT) is one of the most reputed institutes in Thailand with an average population of about 3,800. The daily amount of the solid wastes generation in AIT is around 2000 kg and about 60 % of the waste stream comprises of organic fraction which are disposed to the landfill (Shamit, 2007). The treatment methods employing for AIT solid wastes are recycling (4% of total waste), composting (3% of total waste) and landfilling (93% of total waste) Therefore, the separation of the organic fraction of AIT solid waste was introduced. Accordingly, separate collection of organic wastes was done with the support from Swedish International Development Co-operation Agency (SIDA). This included separation of the organic fraction (also known as green waste) and non-biodegradable waste. Experience has shown that this method of separation provides the best quality product in terms of heavy metals and plastic contamination. The segregation of wastes allows to be treated, recovered or reused, or disposal of the wastes in more environmentally and economically sound manner.

Under this programme, 3RKH was emphasizing on door-to-door waste collection and segregation of waste. After continuous efforts, the door-to-door waste collection system had started with 20 households and other potential sources. The amount of organic wastes collected from these sources are presented in Appendix F. Figure 4.1 presents amount of organic wastes generated from selected sources in AIT which shows that the maximum amount of wastes were generated from cafeteria (60%) and was the least from the 20 households (10%). Before initiating the project, no such system of waste management existed in AIT and people were not aware about the segregation of organic and inorganic materials.

For segregation of the organic fraction of the wastes, some representative households were selected as per their interest on segregating the wastes. According to this activity, the garbage bins (grey color) were first distributed to the selected sources depending on the amount of waste they generate. After distributing the garbage bins, the instructions about the waste sorting were given to all along with the poster. Two types of bins were provided for separating biodegradable and non-biodegradable fraction of wastes and the wastes were collected daily to avoid the odor problem. Indeed, even source separated organic AIT solid wastes required some further separation to remove wrongly sorted materials such as plastics, cans and larger sized materials. Finally, the biodegradability of OFMSW was used to assess the gas production.

According to Shamit (2007), more than 60% of the total wastes generated in AIT are biodegradable having higher moisture content (>70%). In general, if the material predominantly is kitchen waste, anaerobic digestion is the most appropriate method (Braber, 1995). Part of the organic fraction of the wastes is being treated by composting in AIT. But it is seemed that the anaerobic digestion is more suitable technology to treat the existing characteristics of the wastes. Thus, the segregated organic fraction of the wastes was employed for the production of biogas and minimization of the waste using anaerobic digestion process.

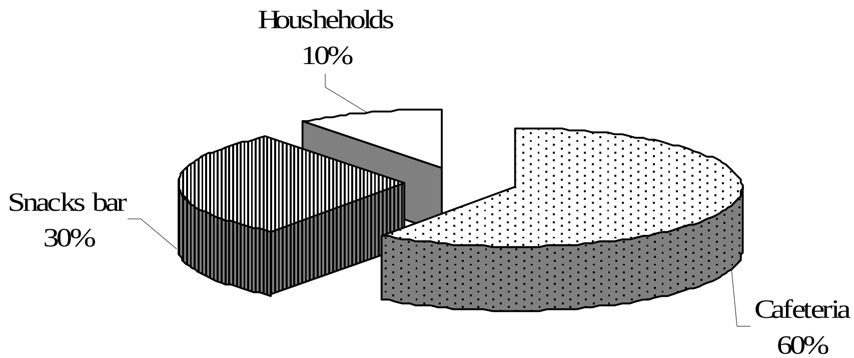


Figure 4.1 Organic waste generation from selected sources in AIT

Although various pretreatment and conditioning procedures such as chemical and enzymatic hydrolysis or particle size reduction have provided some improvements to methane yields (Mata-Alvarez et al., 2000). Another problem that can affect the utility of anaerobic digestion has been the content of residual heavy metal and other forms of contamination in the organic product, especially when processing has been applied to mix MSW (De Baere, 1999). While source separated organic wastes can alleviate this problem.

Waste segregation is something which without proper support from the people cannot be achieved. Thus raising awareness among the people towards waste segregation and minimization is extremely important.

4.2 Continuous anaerobic digestion reactor

4.2.1 Feedstock preparation and analysis

The MSW used for this study was obtained as source-separated food waste from cafeteria and selected households that covered 20 households. The waste was kept in cold room at a temperature of $5^{o}C$ to avoid the degradation of the waste. Before being loaded to the reactor, food wastes must undergo some pretreatments (Bouallagui et al., 2005). They were shredded to small particles with average size of 10 mm and homogenized to facilitate digestion. The sub-samples were dried and milled to the millimeter size and analyzed for moisture content (MC), total solids (TS) and volatile solids (VS) using standard methods (APHA, AWWA & WEF, 1998). The characteristics of the waste used in the experiment for lab-scale and pilot-scale systems are shown in Table 4.1 and Table 4.2 respectively.

Anaerobic sludge used as inoculum was collected from an anaerobic digester of wastewater treatment plant. The feedstock was prepared with the mixture of food wastes, fruit waste and boiled rice in order to obtain the desired loading rate and optimum C/N ratio.

Table 4.1 Characteristics of raw shredded solid waste and inoculums

Sample	Moisture content (%)	Total solid (% TS)	Volatile solid (%)
Food waste	81.20	18.80	77.60
Anaerobic sludge	92.55	7.45	44.35
Digestate	87.22	12.78	45.39
Cow dung	81.57	18.43	77.81

Table 4.2 Characteristics of solid waste during continuous loadings

	Loading 1	Loading 2	Loading 3
Moisture content (%)	81.31	82.62	78.32
Total solids (%)	18.69	17.38	21.68
Volatile solids (%)	84.07	77.86	83.17
C/N ratio	20.52	21.01	21.96

Table 4.1 and 4.2 show that the percentage of moisture content is higher in the food waste due to presence of high fraction of fruit peels and vegetables. For the anaerobic digestion process the nutrients proportion should be suitable for the microbial growth. According to Stroot P.G. et al. (2001), the suggested optimum C/N ratio for anaerobic digestion is in the range of 20:1 to 30:1. The C/N ratio of the food waste was found to be 20.2 which were suitable for the AD process. During the digestion process, much of the organic matter in waste is converted to volatile fatty acids by acidogenic bacteria, and these VFAs are then consumed by methanogenic bacteria to produce methane, carbon dioxide and other few gases. Nitrogen, phosphorus and potassium are transformed by these microbial processes, but these nutrients are not destroyed. The Table 4.3 indicates macro nutrients in feedstock which is similar to Castillo et al, (2006) reported.

Table 4.3 Nutrient analysis in feedstock

Parameters	**OFMSW**
N(%DW)	2.06
P(%DW)	0.15
K(%DW)	0.13
C (%)	43.59
C/N ratio	20.15
Calorific value (MJ/kg)	14.3

4.2.2 Phase 1: Reactor start-up

The reactor was initiated with the fresh waste of 270 kg which was 80% of the reactor volume. From the measurement the density of the waste was around 700 kg/m^3. The total volume of the reactor was 690 L and the total weight of the waste fed including inoculums was 387 kg in which 30% of waste was inoculums. The reactor was operated in batch mode for 8 weeks for start-up process. The inoculum was comprised of cow dung, anaerobic sludge and digestate. The ratio of these inoculums was 2:1:1 (Eliyan, 2007; Adhikari, 2006; Jean, 2005). Homogenization of fresh wastes with inoculums was done properly before feeding into the system. The composition of waste was 270 kg fresh solid wastes, 58 kg cow dung, 29 kg anaerobic sludge and 29 kg digestate. To avoid the risk of thermal shock inside the reactor, the reactor was started with mesophilic temperature 37^{o}C and the temperature was gradually increased to a thermophilic temperature 55^{o}C by increasing 2^{o}C daily. The main feature of this system was to avoid the use of leachate for the mixing. To enhance the biodegradability of the substrates, the mixing was performed by circulating the waste inside the reactor.

a. Biogas generation and quality

Digestion during start-up ran for a total of 56 days, during that period start-up reached methanogenesis, characterized by high methane composition (>60%). Figure 4.2 indicates the daily and cumulative biogas production where the biogas production was high in the beginning which was due to the entrapped air inside the reactor and the waste itself because the methane composition during that period was almost zero. High biogas production and methane yield was obtained during circulation of the wastes inside the reactor. From figure 4.2 and 4.3, it is clear that the biogas production and methane composition was lower between 12 and 22 days because there was no circulation of the waste and these components were increased on initiating the circulation of the waste.

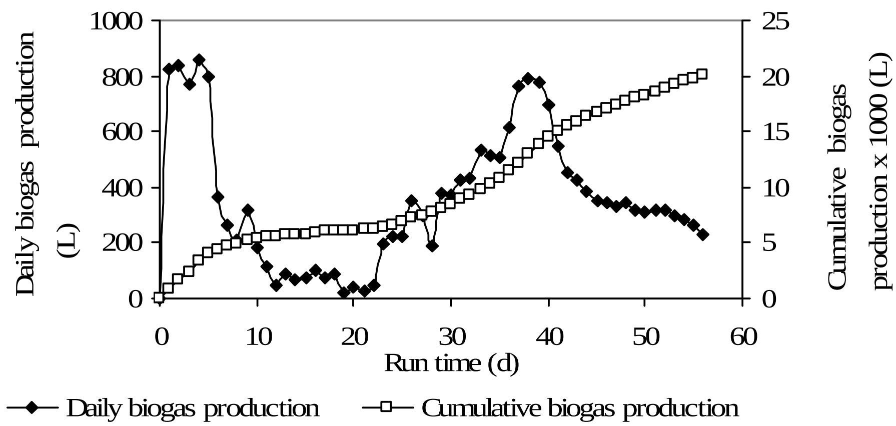


Figure 4.2 Daily and Cumulative biogas production during start-up

Mixing affected the time taken to establish methanogenesis in the start-up, as methanogenesis started gradually on mixing and reached maximum between days 31 and 45. The longer start-up period was attributed to the heterogeneity of the inoculum. The highest volume of biogas produced (791.9 L/d) was achieved at day 38 and the methane composition was reached to a maximum value of 66.68% (Figure 4.3) at the same day (Appendix D-1). The biogas production rate fell after day 39 indicating exhausting of readily accessible substrate for biogas production. The reactor system was run until the gas production rate peaked and then dropped below 200 L of gas per day. Then, the feeding and withdrawing mode of operation was started.

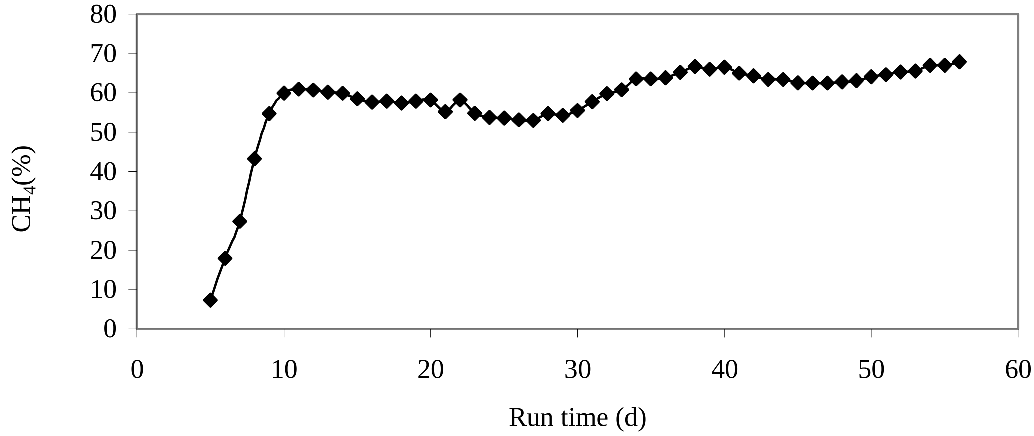


Figure 4.3 Trend of biogas composition during reactor start-up

b. Leachate characteristics

The pH and alkalinity variation are shown in Figure 4.4 in which the pH was at a lower value below 7 during first 10 days. This was due to the formation of organic acids e.g. volatile fatty acid. The alkalinity was also found lower and reached to around 1500 mg/L as $CaCO_3$. Due to lower alkalinity and pH, the methanogenic activity was not initialized and the composition of methane was below 50%. The pH of the leachate was monitored and an attempt was made to keep it above 6.5 by the addition of commercial NaOH. On days 5, 7 and 9, 1.5 kg of NaOH were added. From day 10 to 30, the pH and alkalinity was almost found steady. Despite of steady pH and alkalinity, the biogas gas i.e. methane production was low during that period due to lack of mixing.

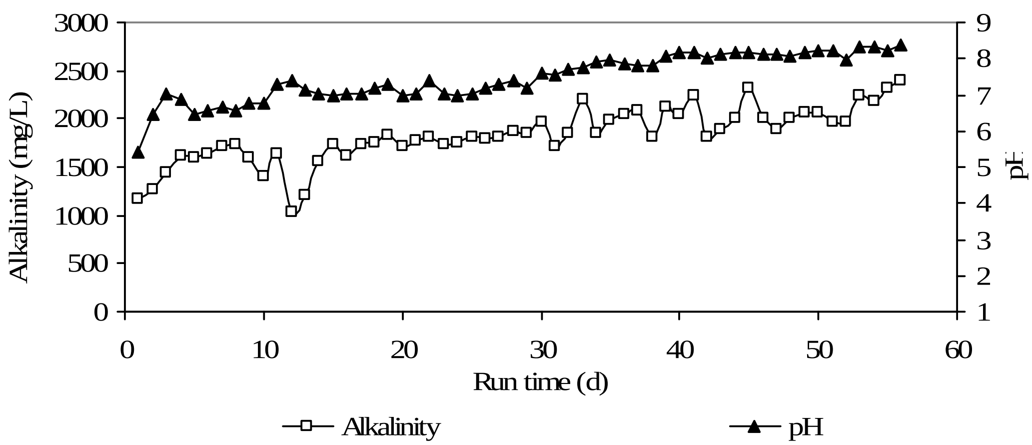


Figure 4.4 Variation between pH and alkalinity

So the mixing by circulation of waste inside the reactor was performed and both pH and alkalinity was found increased. The pH reached above 7.5 but not exceeded 8.5 which are inhibiting condition for methanogenesis. During that period, the biogas production as well as methane composition was reached the maximum value of 791.9 L/d and 66.68% respectively.

Figure 4.5 shows the variation of volatile fatty acids (VFA) concentration during start-up period. The VFA generation in the beginning was high due to higher acidogenesis and lower methanogenic activity. As the food waste consists of highly putrecible fraction, they were degraded quickly and the concentration of VFA was found elevated. The VFA production between days 1 to 30 was found around 3000 mg/L which was lower than inhibition concentration and the pH was also found between 6 to 7. After day 30 the VFA concentration was found decreased due to methanogenic activity in which the intermediate organic acids was started to convert into biogas such as methane and carbon dioxide. The VFA concentration reached around 1500 mg/L after day 30. The principal volatile acids formed were acetic and propionic acids. The pH dropped in the beginning, corresponding to the transient accumulation of volatile acids, but then increased as the VFAs were converted to methane.

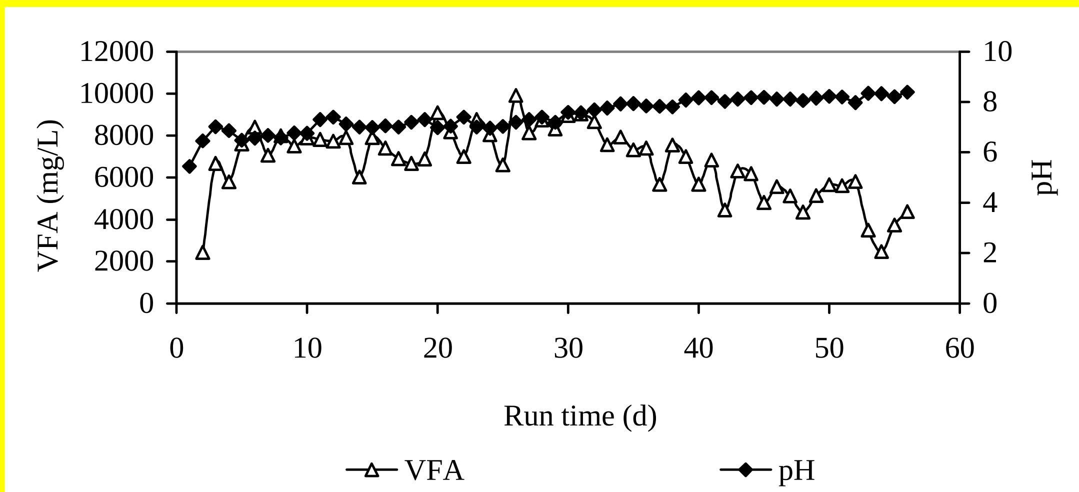


Figure 4.5 Trend of VFA concentration and pH

The organic content of substrate was measured in terms of Chemical Oxygen Demand (COD) and Dissolved Oxygen Carbon (DOC). The Figure 4.6 depicts the variation of these parameters during start-up process. The significant increase in COD in leachate was observed in the beginning which was the sign of active hydrolyze phase. The COD and DOC of the leachate were found decreasing due to conversion of organic mater into biogas and the trend of COD and DOC with retention times were found similar so the DOC can be used as a measuring parameter to estimate COD.

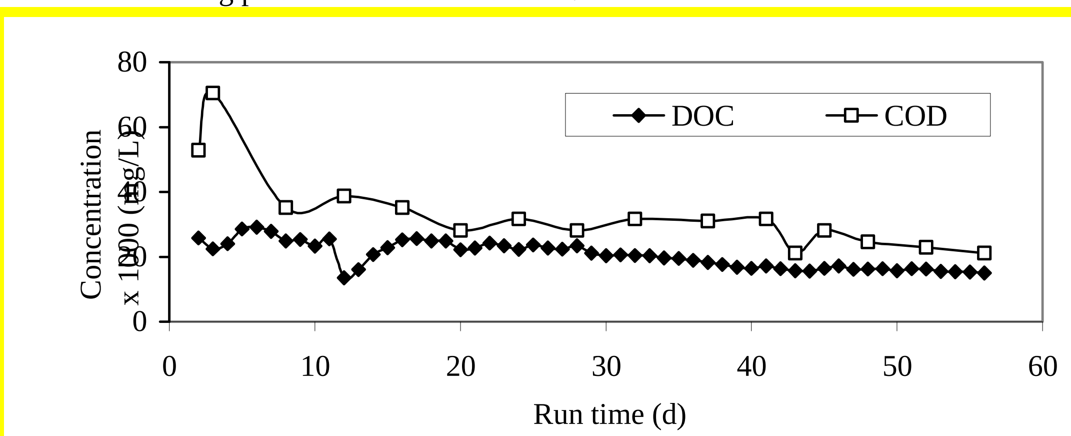


Figure 4.6 Variation of COD and DOC during star-up operation

As shown in Figure 4.7, the TKN concentration at steady state was slightly different than the first 2 weeks. This was attributed to release of ammonia during hydrolysis of protein or utilization of nitrogen for biomass synthesis. It is evident that NH_4-N concentration (>6000 mg/L) indicates the inhibition of methanogens in an acclimated environment (Mata-Alvarez, 2000). In this study, the NH_4-N concentration increased from 980 mg/L to 3360 mg/L and pH was also found above 7.5 (Appendix D-2) which was below the inhibition limit.

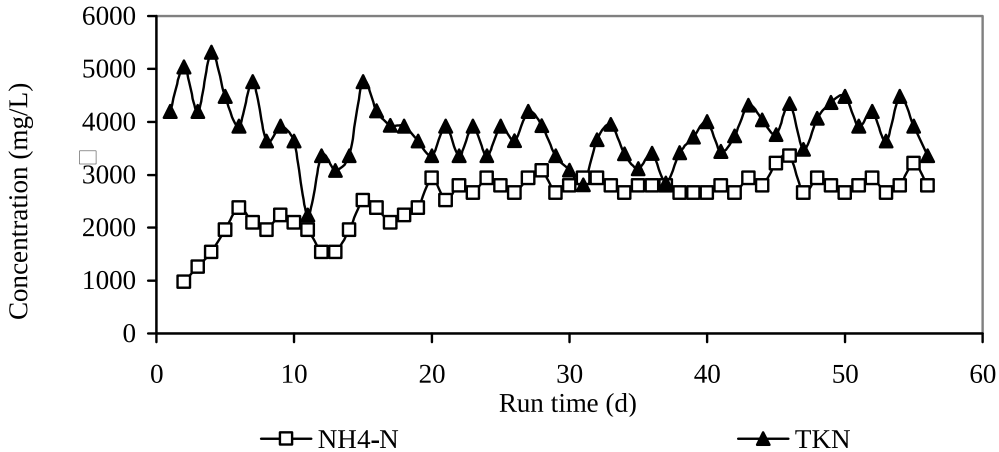


Figure 4.7 Trend of NH4-N and TKN during start-up process

4.2.3 Phase 2: Continuous feeding

This is the final and continuous phase of operation. In this operation, the continuous feeding was applied in draw and feed mode. Experiments were conducted for three different organic loading rates of 2.5, 3.3 and 3.9 kg VS/m^3.d for constant retention time of 25 days. The experimental runs at phase 2 were carried out in a sequentially scheduled routing beginning with 2.5 kg VS/m^3.d. Once the reactor was operated for the required number of days as determined from the retention time, another loading rate was started. Three such loading rates and retention time used for these experiments are shown in Table 4.4. The operational days were at least equal to the retention time. Retention time is a measure of the time that the substrate spends inside the digester. The working volume of the digester was maintained at approximately 80% and a proper volatile solids balance were done as explained in Chapter 3 (section 3.2.2).

Table 4.4 Loading schemes for continuous operation

Descriptions	Loading rate (kg/d)	Organic loading rate (kg VS/m^3.d)	Retention time (days)
Loading 1	9	2.5	25
Loading 2	13.5	3.3	25
Loading 3	12	3.9	25

a. Biogas and methane production

Biogas samples for analysis were collected and analyzed. One of the main objectives of this research was to determine the performance of the AD process when operated at different loading rates. For this reason, it was highly important to evaluate process performance in term of biogas composition and production to various loading rates. The experimental results showed the variation of the biogas production during loading rates 2 and 3 whereas it was found to some extent similar in lading rate 1 (Figure 4.8). The daily biogas production obtained during loading rate 2 and 3 were approximately 780 L/d and 670 L/d respectively whereas the daily biogas production in loading 1 was found approximately 635 L/d (Appendix D-3).

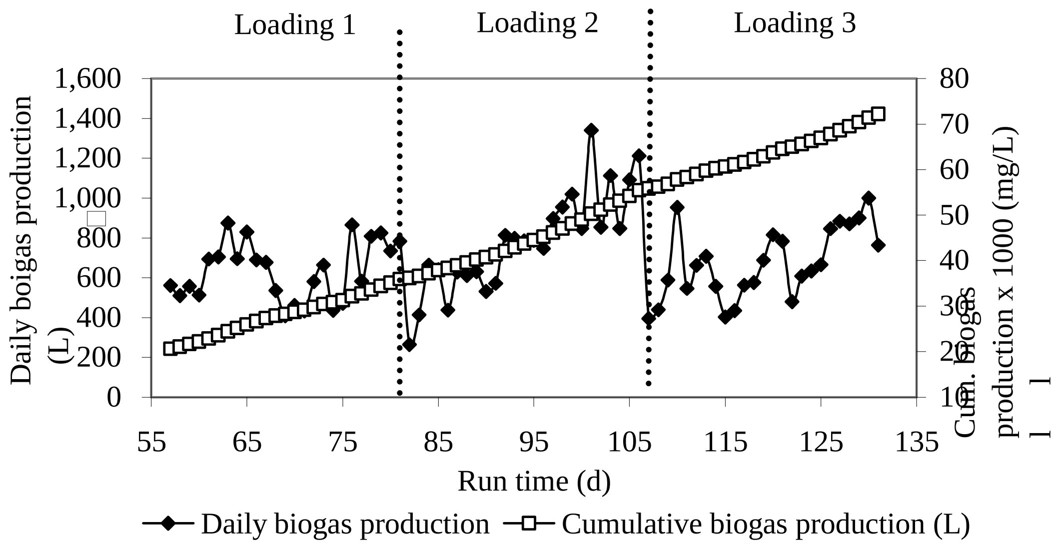


Figure 4.8 Daily and cumulative biogas production during Loading rate 1, 2 and 3

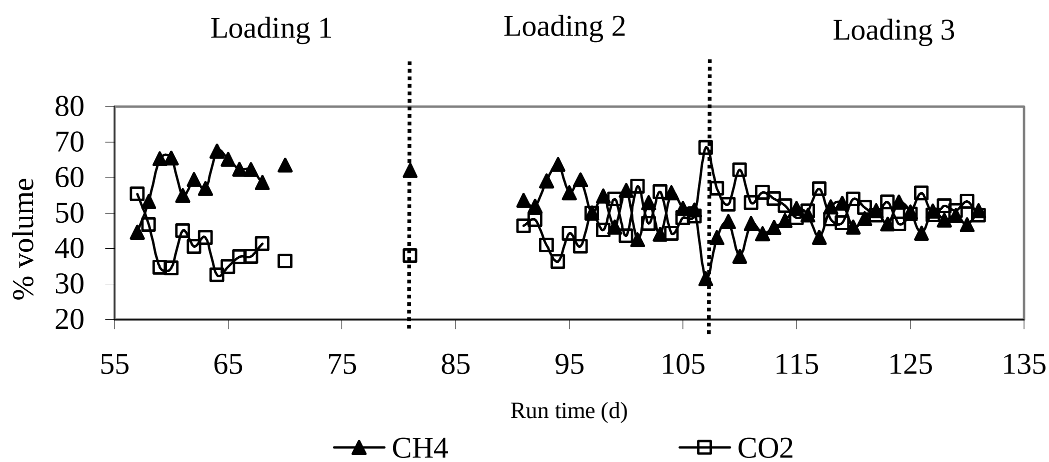


Figure 4.9 Variation of biogas compositions during loading rates 1, 2 and 3

Methane concentration in biogas was observed around 60% (Figure 4.9) in loading rate 1 and was observed 53% in loading 2 whereas it was found less than 50% in loading rate 3 (Appendix D-3). The measurement of the quantity and composition of the biogas produced in terms of methane and carbon dioxide content is of fundamental important to evaluate the performance of the process. As carbon dioxide in biogas was found increasing means that the acidifying microorganisms are prevailing on the methanogens that may lead to VFA accumulation. From the fact finding of this study, carbon dioxide was produced from acidification of the system. This statement was proofed by comparing the methane concentration during the first few days of operation. For this reason, indication of unsteady state of the reactor was occurred during loading rate 3. As the variation of the biogas production was minimum and methane concentration around 60%, the loading rate 1 can be said as the optimum loading rate for the stable operation of dry continuous anaerobic digestion process of the existing reactor configuration.

b. Leachate characteristics

The stability of the reactor performance was investigated through leachate characteristics analysis besides biogas production and composition. In the anaerobic digestion process, methanogenic bacteria is more sensitive to environmental conditions than hydrolytic and acidogenic bacteria. The first criteria was taken into account was pH value. The pH of effluent from leachate indicates the stability of the system and its variation also depends on the buffering capacity itself (Mata-Alvarez, 2003).

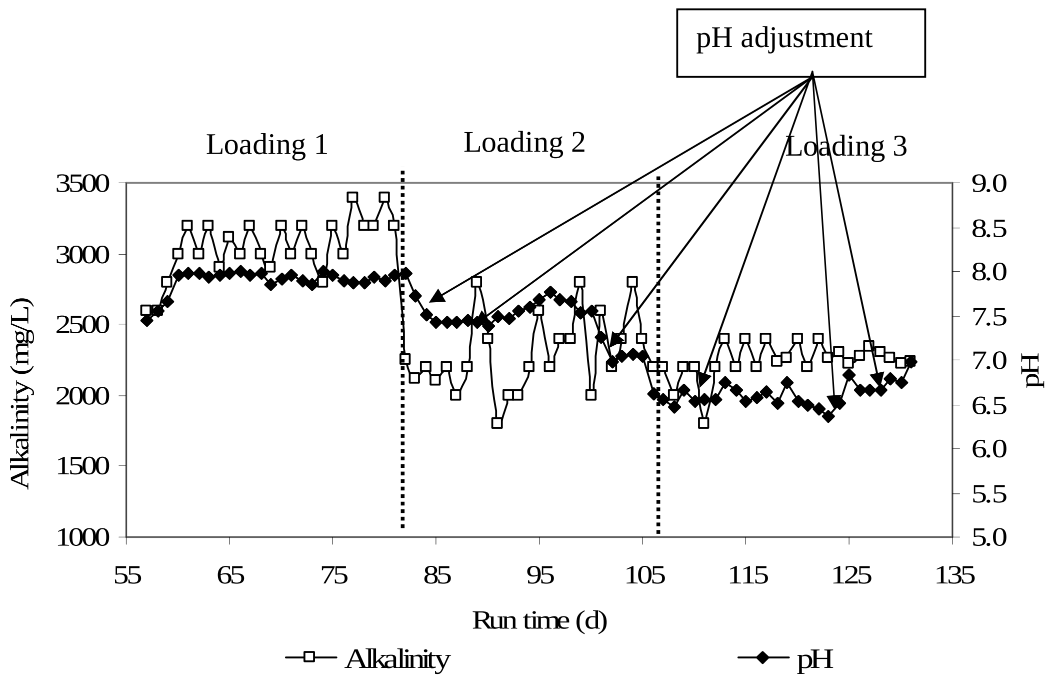


Figure 4.10 pH and Alkalinity during continuous feeding

The pH is an indicator of good process performance and should be above 7.0 at all times in which case the process operates successfully. The pH of effluent leachate from the continuous digester remained steady state to the range of 7.5 - 8.0 during the loading rate 1 (2.5 kg VS/m^3.d) which shows that the system was well buffered (Figure 4.10). When the loading rate was increased to 3.3 kg VS/m^3.d, the pH value dropped from 7.5 and reached to lower value of 7.0 but it was still above 7 which were in the methanogenic range. The methane content in the biogas dropped and the system showed sign of overloading. As the pH was in the methanogenic range, the methane content in the biogas was above 50%. Figure 4.10 illustrates that the pH in loading rate 3.9 kg VS/m^3.d was dropped from 7.0 to 6.0. Since the pH is controlled by the volatile organic acids concentration, the alkalinity showed similar trends. This was resolved by immediately stopping the feeding and adding alkaline solution. But the condition could not be recovered during loading rate 3.

Figure 4.11 presents the variation of COD and DOC concentrations in leachate. In loading rate 1, these concentrations were found significantly decreased after the completion of the retention time. But COD and DOC in leachate were found at the higher concentrations in loading rate 2 and 3 during the digestion. This can be explained that there was higher hydrolysis but less methanogenesis because hydrolytic bacteria are more robust to environmental condition. As the organic loading rate was increased, the COD degradation decreased.

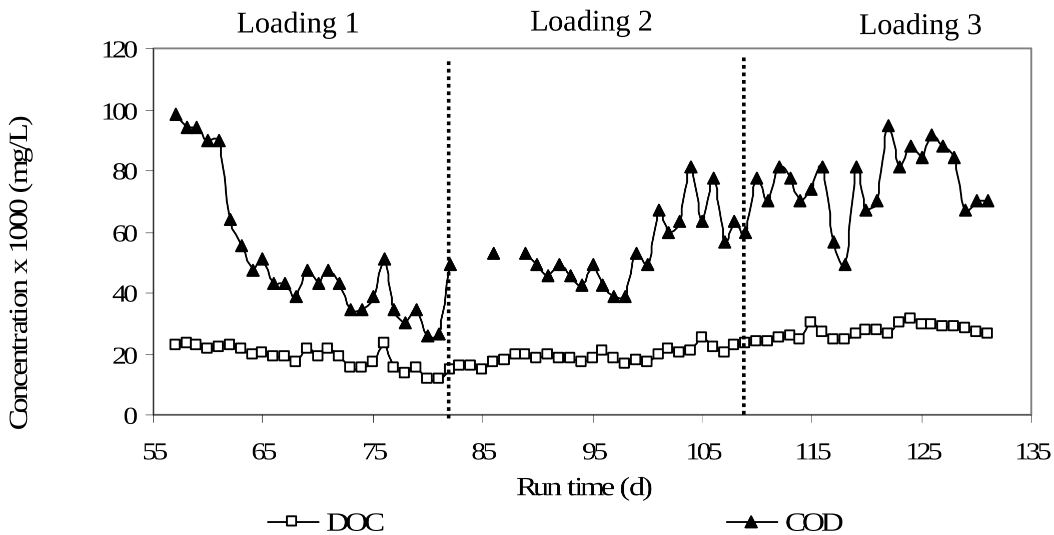


Figure 4.11 Variations of COD and DOC

The presence of ammonia nitrogen can always be of concern in anaerobic digestion as free ammonia can be inhibitory. Ammonia (NH_4-N) is the end product of anaerobic degradation of Proteinous materials. Protein first converted into amino acid in hydrolysis stage, and then further degraded anaerobically in acidification stage producing ammonia.

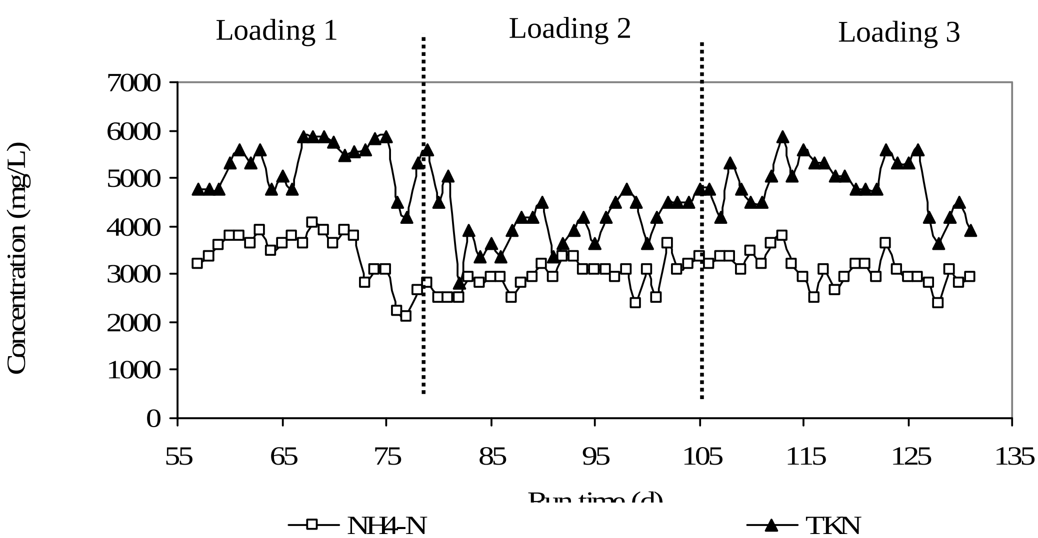


Figure 4.12 TKN and NH4-N during continuous feeding

In this experiment, concentrations of NH_4-N were high during loading rate 1 and were at the level of 3700 mg/L (Appendix D-4). But these concentrations were lower in loading rates 2 and 3 due to falling of pH value and less degradation of proteinous materials (Figure 4.12). The inhibition concentration of ammonia nitrogen as reported by Mata-Alvarez, 2000 is 6000 mg/L which is higher than the ammonia concentrations obtained in this experiment. So it can be concluded that there was no any inhibitions of ammonia nitrogen during the AD process of this system.

4.2.4 Overall process performance

Anaerobic digestion system for digestion of MSW is now widely used throughout the world. In this experiment, the dry continuous anaerobic digestion of OFMSW in pilot scale was conducted over a period of 10 weeks. The reactor was a complex black box (closed system) operating different stages of fermentation at a given time. However, the purpose of assessing the effect of loading rates upon the system was obtained once the biogas generation peaked up and stabilized for loading rate 1.

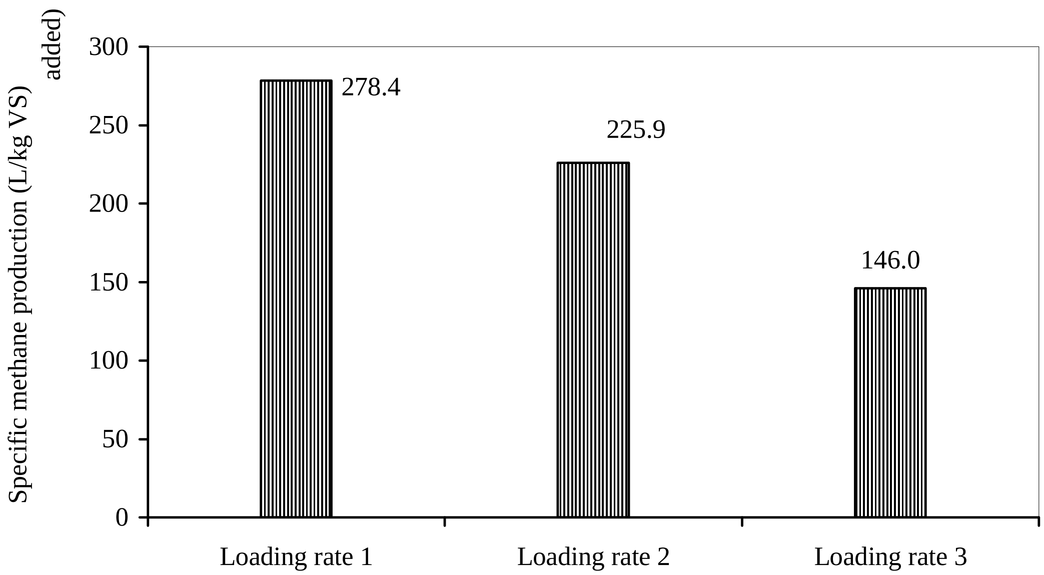


Figure 4.13 Profile of specific methane production for various loading rates

Anaerobic digestion process which was used in this research is relatively a simple option. Nevertheless, operating the pilot scale equipment for more than 6 months gave a practical experience and revealed the difficulties with anaerobic digestion since the process itself is very complicated and very sensitive to be upset during the start up period. Therefore, it is not that easy task to give corrected conclusions according to the variation of loading rates and assess each loading rate in terms of biogas yield, quality as well as the quantity. For the purpose of evaluating this system on the effect of loading rate, VS reduction, biogas composition and specific methane production were taken into account as the indicators to assess the reactor performance and efficiency of each loading rate.

To further the investigation, Specific Methane Production (SMP) for various loading rates is presented in Figure 4.13. The highest specific methane production observed was 278.4 LCH_4/kgVS in loading ratev1 (2.5 kg VS/m^3.d). As the loading rate was increased, a gradual increase in the amount of biogas production (780L/day and 670 L/d in loading rate

2 and 3 respectively) was observed, accompanied by a decrease in the methane yield (225.9 L CH_4/kgVS and 146.0 L CH_4/kg VS).

The loading rate (3.9 kg VS/m^3.day) reported here should be interpreted in line with Mata-Alvarez et al. (1992) who mentioned that higher biodegradability of the wastes means larger and faster VFA production which stress the validity of the organic loading rate (OLR) limit. It should be cautioned here that the optimum loading rate of 2.5 kg VS/ m^3day observed here is not universal as the optimal rate depends upon the reactor configuration (Cecchi et al. 2003). The specific methane yields obtained were 278.4, 225.9 and 146.0 L CH_4/kg VS for loading rates 1, 2 and 3 respectively. These values correspondence to 87 % , 70.59 % and 45.63 % process efficiency calculated based on the laboratory BMP assay (320 L CH_4/kg VS). The overloading was marked by the fall in pH and gas yield and increase of carbon dioxide content in the biogas. In this study, the best results were obtained with an organic loading rate of 2.5 kg VS/m^3.day.

Volatile solid reduction was taken into account as well to evaluate the reactor performance and stability of the digestaste. VS degradation value of 59.21 % was achieved when operating loading rate 2.5 kg VS/m^3.d. On the other hand, while loading rate 2 and 3 with increased loading rates of 3.3 and 3.9 kg VS/m^3.d, VS removal were decreased to 54.39 % and 39.53 % respectively as illustrated in Figure 4.14 (Appendix E). Comparably, these VS reduction was lower with result found by Castillo et al. (2006) who reported that VS reduction of 77.1% was obtained with the digestion time of 25 days.

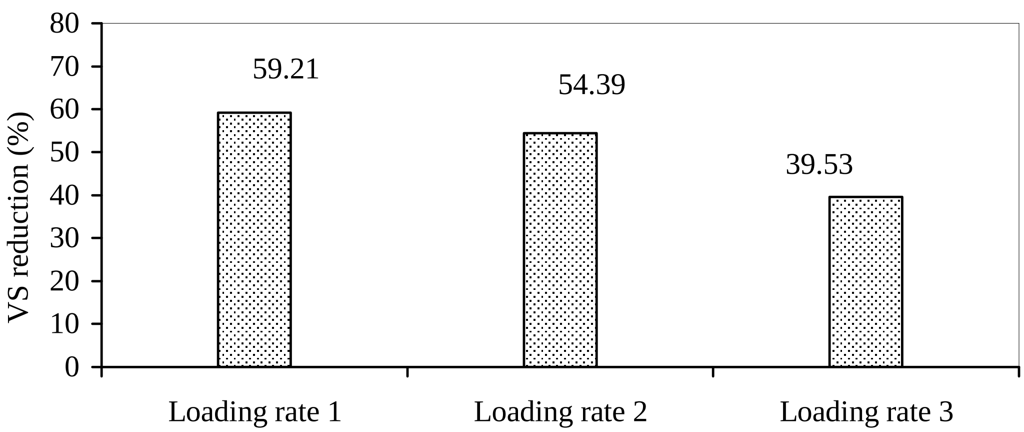


Figure 4.14 VS degradation for various loading rates

4.3 Post-treatment of digestate

The primary digestate after 25 days digestion was removed from the digester and processed through sludge drying bed. Following AD, the fresh digestate had a typical solids content of 5-10%. In anaerobic digestion treatment plant, the digestate was dewatered to reduce the weight and volume of digestate that must be transported for disposal. The dewatered solids would then be either composted or used as a soil amendment. In this experiment, the effluent from the AD system was analyzed and was found removal of COD around 45%. It is recommended that effluent leachate (percolate) should be sent to the wastewater treatment plant or subjected to UASB for the biogas production because the effluent liquid still had high pollutant loadings such as COD.

If the digestate is not treated using solids separation, the material will have about 10 % TS and 90 % moisture content. This material would find use as a liquid fertilizer for the producers if sufficient land could be found. Sludge drying bed serve to effectively separate solids from liquids and to yield a solids concentrate. In present study, the sludge drying bed dewatered the residue to 50% TS (dewatered digestate) and 2% TS (percolate). Gravity percolation and evaporation are two processes responsible for sludge dewatering and drying.

In contrast to settling and thickening of digested sludge, dewatering and drying of thin layers of sludge drying bed took for comparatively long retention periods. However, organic loads in the percolate of drying bed were significantly lower than in the effluent of AD process (Table 4.5). Hence, less extensive further treatment of percolate will be required. From 80-90% of the digested sludge volume applied to sludge drying bed emerged as drained liquid (percolate). According to this experiment, maximum allowable solids loading rate (7.58 kg TS/m^2) was applied with a sludge application depth of 10 cm to attain a 50 % solid content over a drying period of 15 days. In this study, the total weight of dewatered digestate was found 39 kg which is 52 % weight reduction of fresh digestate (Appendix G). The post treatment stage was used to remove contaminants and change the output into a suitable form for its end-use application. The extent of post treatment depends on the end-use application for the material such as compost soil improver, recovered fuel or landfill.

The main objective of this study was to examine the present dewatering facility and to measure the pollutant levels (COD) in the produced percolate in order to assess the overall performance of the sludge drying bed. This was important because of the problems associated with fresh digestate. The results from the SDB showed that the organic matter decreased over period of times due to removal of suspended particles. But the time taken to obtain the thickened sludge was longer due to clogging of the sand layer.

4.4 Digestate quality

Digestate is the effluent coming out from the digester at the completion of the digestion process. Digestate has nutrient value and can apply digestate to land, much like manure. The digestate from anaerobic digesters usually contains about the same amount of nutrient as in the feed materials for the digesters. However, nutrients in the digestate are in a more readily available form for plants. Therefore, farmers can apply digestate to land, like manure. However, the land application of digestate should meet the allowable nutrient loading levels recommended.

Apart from biogas, the AD process also produces solid and liquid by products which can have a value as a fertilizer or soil amendment. The amount, quality and nature of these products depend upon the quality of the feedstock to the AD process, the method of digestion and extent of post treatment refining process. The main product of AD process is a solid digestate which can be matured into a compost product (Biocycle, 1996).

The chemical properties are the nutrients content (NPK) which needs to be known so that the digestate can be part of the integrated fertilizer. Digestates are rich in phosphorus and when using it appropriate reductions in the phosphorus and to a lesser extent nitrogen application from chemical sources are needed (IEA, 2001). Table 4.6 illustrates the nitrogen, phosphorus, potassium, and carbon value in digestate sample from this research.

Regarding these analysis results as obtained are similar to Kayhanian & Rich, 1995, the anaerobic digestion reduced the nitrogen content in feedstock. Likewise, the increasing the phosphorus and potassium was found.

Potassium and phosphorus were higher due to the fact that some solids have been converted to biogas, resulting in higher nutrient concentration. Evidently the recovery and re-use of nutrients (N,P,K) is an important advantage of anaerobic digestion due to the high quality organic fertilizer solid that may be useful in , in addition to the recovery of energy because landscaping efforts or even crop production it contributes indirectly to a reduction of greenhouse gas emissions. Another, important feature is C/N ratio. All nutrients analyzed in this study were matched with Thai guideline to be used as organic fertilizer as depicted in Table 4.5.

Table 4.5 Nutrient analysis of digestate

	Nutrients (%DM)			C (%)	C/N	Calorific value (MJ/kg)
	N	P	K			
Thai guideline	1	1	0.5		<20	15
Digestate	1.20	0.45	0.40	22.15	18.46	12.1

Source: Rattanaoudom, 2005, cited source: Land development department, Thailand

Depending on their source, biowaste can contain pathogens, which can lead to the spreading of human, animal or plant diseases if not appropriately managed. The physical standards of composts include mainly appearance and odor factors. Whilst physical contamination does not present a problem with regards to human, plant or animal health, contamination (in the form of plastics, metals and ceramics) can cause a negative public perception. Even if the compost is of high quality and all standards are met, a negative public perception of waste-based composts still exists. The presence of visible contaminants reminds users of this. The sale of digestate is a potential additional source of revenue for the operators of anaerobic digestion plants. It has the potential advantage over undigested manures and slurries that it is consistent in nutrient content and availability. This makes it easier for farmers to calculate the correct fertilizer applications to crop requirements compared with using manures and slurries. This reduces the risk of leaching and run off and so can prevent diffuse water pollution. It can replace mineral fertilizer, the production of which requires significant energy input. In this way it can provide additional benefits in terms of reducing greenhouse gas emissions. This digestate has a potential as a fertilizer on farmland. However, one concern is the content of organic pollutants in the digestate, as these may influence the soil fertility in the long-term perspective.

4.5 Biochemical Methane Potential (BMP) test

Biochemical methane potential assays were conducted on several representative solid waste components to determine the ultimate biodegradability and conversion efficiency. These data, shown in Appendix F, indicate that conversion was completed in about 50 days. For interpreting these data, it is important to realize that the ultimate methane yield is influenced by the biodegradability of the feedstock.Biochemical methane potential (BMP) were conducted to estimate the extent and the rate of anaerobic conversion. The biological approach for determining methane potentials lead to substantial uncertainty in the determination. So triplicates samples were used as a minimum. The methane potential of the sampled OFMSW was tested in triplicate by laboratory-scale anaerobic batch tests described in Hansen et al., (2004). The methane potential is defined as the maximum of methane produced during 50 days of the experiment as reported in Gunaseelan, 2004. The anaerobic digestion of MSW having high methane potential and biodegradability is estimated to be an attractive approach for the reduction of its volume with methane recovery.

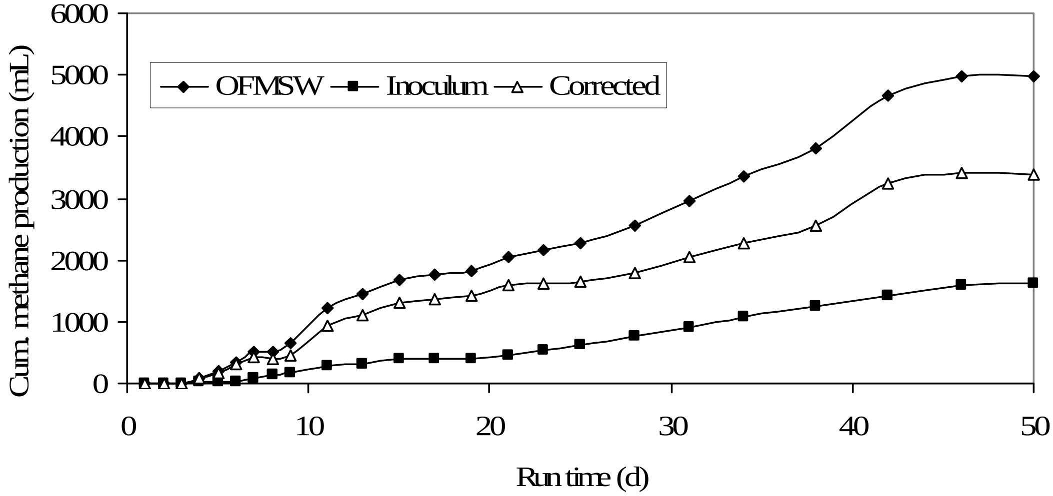


Figure 4.15 Cumulative methane production curves measured for OFMSW and blank

The test was conducted in 2.5 L reactors with its cover and rubber stopper to make it air tight and easy for sampling. Triplicate bottles were assayed for BMP using a sample concentration of 2 g VS/L. Each assay was accompanied with organic fraction of municipal solid waste and blank containing only inoculated medium. Inoculums were prepared with anaerobic digestion sludge from wastewater treatment plant.

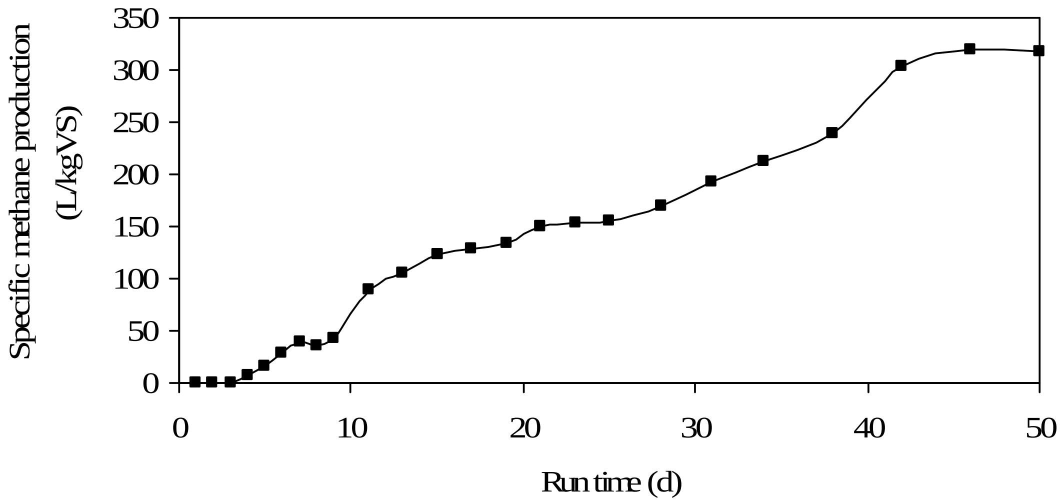


Figure 4.16 Specific methane production curve for OFMSW

The reactors were kept at 55°C and were shaked regularly. Gas samples (0.2 ml) were taken from headspace of the reactors through the rubber stopper with a syringe. Based on the volume of the headspace of each reactor and CH_4-content per 0.2 ml of headspace measured directly on the GC, the produced amount of methane was determined. The measurements, including the gas releases, were transferred into accumulated CH_4 as a function of incubation time. The methane production from the inoculums (blank) was subtracted from the methane production of the waste samples (Figure 4.15) (Appendix J). The result thus represents only the methane production from the waste and not from the inoculums.

The test ran for 50 days. The results of the test data has been shown in appendix A. the graphical presentation of the BMP potential of the organic fraction of MSW are indicated in Figure 4.14 where the methane potential of OFMSW have been reached to a value of 320 L CH_4/kg VS. This shows that the potential of SS-OFMSW is higher than that of the commingled solid wastes as reported in earlier studies (Eliyan, 2007; Radha, 2006). From Figure 4.16, it is concluded that the specific methane potential increased rapidly after day 30 and stabilized at day 50.

4.6 Mass balance

Mass balances were conducted for volatile solids for loading rates 1 (2.5 kg VS/m^3.d), 2(3.3 kg VS/m^3.d) and 3(3.9 kg VS/m^3.d). Table 4.6 presents the mass balance of volatile solids in three different loadings. Which describes that the conversion efficiency obtained during loading rate 1 was the highest compared to loading rates 2 and 3. Figure 4.17 presents the typical mass balance system for loading rate 1. The daily amounts of feedstock to be fed and residues to be withdrawn are described in Appendix I.

Table 4.6 Mass balance system

Descriptions	VS in feedstock (kg/d)	VS loss in biogas (kg/d)	Conversion efficiency (%)	VS in Leachate (kg/d)	VS in digestate (kg/d)
Loading 1	1.410	0.810	60.12	0.068	0.500
Loading 2	1.830	0.995	57.14	0.159	0.640
Loading 3	2.160	0.855	41.45	0.011	1.170

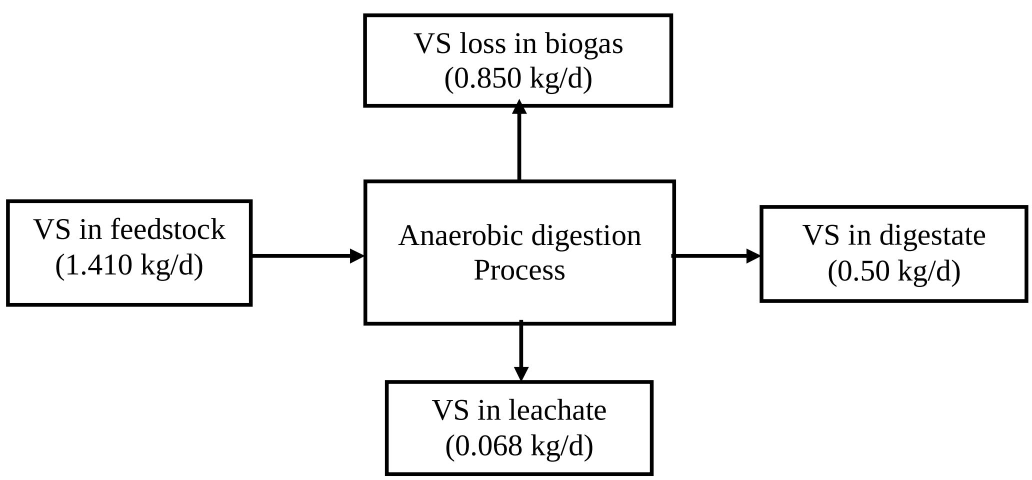


Figure 4.17 Mass balance system during loading rate 1

4.7 Energy balance

Anaerobic digestion is promising means of reducing the amounts of biodegradable waste in MSW stream and is also an energy carrier from renewable resources. The energy produced from the AD system depends on the quality of biogas produced. The biogas quality in turn depends upon the composition of the feedstock. However, the total energy production from digestion as well as the total energy consumption by the system is required to be assessed for the energy balance. In this study, the energy balance was taken into account only during continuous operation (Phase II). The main purpose of observing the energy balance in this experiment is to examine the economy of the energy potential by this reactor. In this calculation, the calorific value of substrate and digestate are also considered for the energy balance of the system.

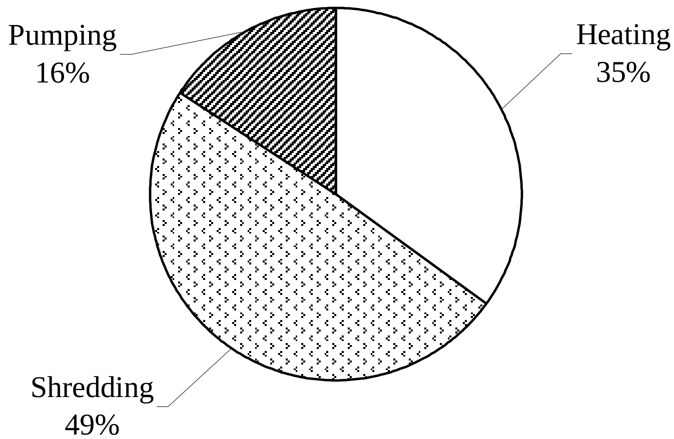


Figure 4.18 Energy consumed in continuous AD system

Table 4.7 represents the energy balance study during three different loadings. The amount of energy consumed at various stages of operation is shown in Figure 4.18. It is interesting to note that the process of shredding consumed of 49% of total energy, heating 35% of total energy and the remaining energy of 16% being utilized by feeding process. To minimize the consumption of energy on shredding, the mechanical shredder should be operated with electric supply.

Table 4.7 Energy balance system

Descriptions	Total VS input (kg)	Energy production (MJ)	Energy consumed (MJ)		Net energy production (MJ)	Net specific energy production (MJ/kg VS)
			Heating	Shredding and feeding		
Loading 1	34.2	341.32	23.72	44.30	273.30	7.98
Loading 2	45.8	369.65	36.78	62.74	270.14	5.90
Loading 3	54.1	282.54	32.64	56.90	193.00	3.53

Figure 4.19 shows the energy expend to produce the biogas. So far, about 80% of surplus energy can be obtained (Appendix B). It can, therefore, be concluded that anaerobic digestion is a net energy gaining system which can produce sufficient amount of surplus energy for the system to be economically viable. Energy surplus from this system from continuous operation was estimated to be 80% (Figure 4.19) (the detail calculations are attached in Appendix B) compared to 75% in the previous study (Adhikari, 2006) conducted in vertical continuous operation digester. This is obvious as the system was not being able to maintain the steady state condition during loading 2 and 3 due to overloading in the system.

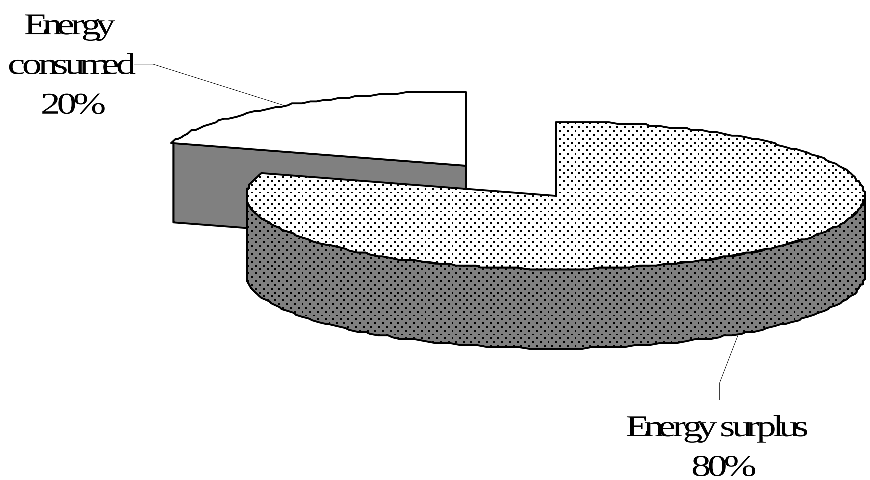


Figure 4.19 energy balances in AD system

4.8 Conceptual framework for AIT solid waste management

An anaerobic digester can be designed based on reactor analysis in this experiment for treating the organic fractions of AIT solid wastes which are now disposed in a landfill.

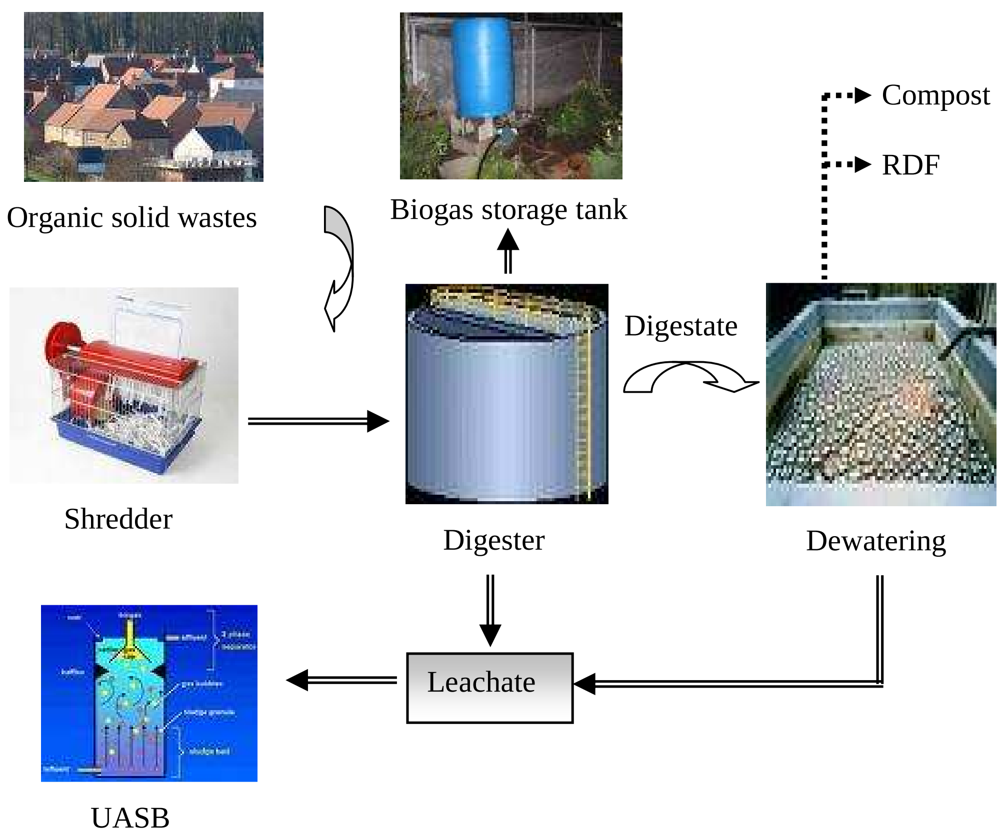


Figure 4.20 Conceptual flow diagram of organic fraction of AIT solid waste

This section analyzes the design, operating system and energy potential of AD treatment plant as well as the impact on reductions of greenhouse gases. The following conceptual diagram represents the framework for the sustainable management of AIT solid waste (Figure 4.20). It specially focuses on the decentralized solid waste management systems. Such plant can be established for the waste management of certain locality in order to reduce the load on central solid waste management system.

According to Shamit, 2007, the daily amount of the solid wastes generation in AIT is about 1900 kg/d which comprises of 60% organic wastes and are well suitable feedstock for the anaerobic treatment technology. As described in section 4.2.4, the optimum loading rate was obtained at 2.5 kgVS/m^3.d that has the maximum methane yield for the existing pilot scale reactor. So this system can be simulated with the treatment of the organic fractions of AIT solid wastes for the sustainable solid wastes management as shown in Figure 4.18.

- **Design of AD treatment plant**

Based on the experimental results, the required volume of the reactor will be 72 m^3 which can be designed with four reactors of 18 m^3 each for the current amount of AIT solid wastes (Appendix F). Anaerobic digestion plant will be equipped with reception and pretreatment facilities for the incoming organic waste before loading into the system. As the feedstock for the treatment plant will be source-sorted organic wastes, the pretreatment process will be only the shredding for facilitating the digestion and pumping. The diameter and height of the inclined (30 ^{o}C) anaerobic digester will be around 3 m and 2.5 m. After the treatment in the digester, the simple sludge bed can be used for dewatering of the solid and liquid fractions in order to use as soil amendment or fertilizer. Table 4.8 presents the simulation of the pilot scale plant with the actual plant for treating the organic fraction of AIT solid wastes.

Table 4.8 Simulation of pilot-scale plant with actual plant

Descriptions	Unit	Pilot-scale plant	Actual plant
Retention time	d	25	25
Daily feedstock	kg/d	9	285 x 4
Digestate	kg/d	2.8	355 x 4
Leachate	L/d	6.2	785 x 4
Volume of the reactor	m^3	0.6	18 x 4
Daily biogas production	L/d	635	10922 x 4

- **Operation of the system**

Feeding and residual removal will be carried out manually once every day. The retention time will be chosen to be 25 days. Before feeding, the waste should be stored for one week and the necessary pretreatment processing should be done for the consecutive week for the proper operation of the system. The biogas composition and pH of the leachate should be monitored regularly to prevent upsetting of the reactor and necessary actions such as decrease of loading rates, alkaline treatment can be taken as a trouble shooting.

As the biogas (energy) can not be stored for a longer period of time, the system should have immediate conversion facility into electric energy. However, the temporary biogas storage tank can be installed. Figure 4.21 shows the typical layout of the AD plant to be installed in AIT for diverting the organic fractions of solid wastes going to landfills.

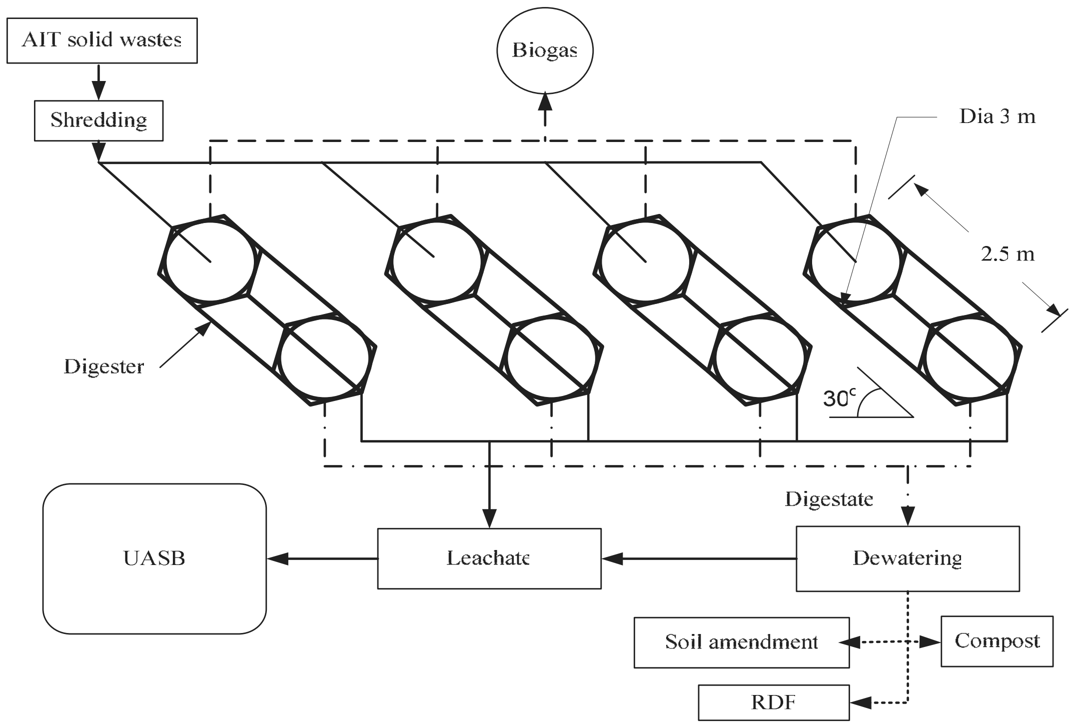


Figure 4.21 Layout of the AD plant for AIT solid waste

- **Energy Potential**

Conversion of biogas to heat and power is a clean and environmentally friendly process. The amount of biogas producing from this plant will be enough for providing the energy for the operation of the system itself and can also provide partial electric supply to AIT community. The daily amount of the surplus energy produced from this system will be 1371.42 GJ (Appendix F). From the analysis of the dewatered digestate , the calorific value of the dewatered digestate was found about 12.1 MJ/kg DW and the production of digestate from this plant will be also high (547 kg/d). So the digestate can also provide 6618.7 MJ energy if they are subjected to Refuse Derived Fuel (RDF) technology (Appendix F). Similarly, the effluent leachate from such plant as obtained in these experiments has high COD and is easy for the UASB reactor for the production of biogas which can be the additional source of energy.

- **Mitigation of greenhouse gases emissions**

The energy conversion itself reduces the global loading of carbon dioxide and methane to the atmosphere from the emission of landfill gases. For the abatement of green house effects, the waste sector can be easily managed requires less effort in comparison to the energy sectors (Ayalan et al., 2000). The reductions of the methane after introducing this biological treatment plant will reduce 159.6 m^3 of CH_4 (Appendix F). So this system has the significant effect on the reduction of greenhouse gases and preventing the unusual climate change.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

From this investigation it is concluded that source sorted organic fraction of municipal solid wastes can be anaerobically digested, producing a biogas containing 50%-60% CH_4 at a rate of approximately 0.464 m^3/kg VS. d. The rate of biogas production observed in the pilot scale digester declined with increasing influent volatile solids concentration and this decline was due to the limited ability of the digester to thoroughly mix the contents and thus avoid the production of scum layer. The mixing capability of the pilot scale digester far exceeded the mixing ability of commonly designed sludge digesters, indicating that new developments in digester mixing are needed for successful digestion of classified MSW.

In this study, pilot scale anaerobic digestion of OFMSW was conducted. An inclined anaerobic reactor was designed and operated under continuous mode. An attempt to optimize the process was done by increasing the loading rate at constant retention time. The following conclusions can be drawn from this study:

- An effective start-up of the anaerobic digestion with inoculum and substrate acclimatization was done successfully. A gradual increase from mesophilic condition at the rate of 2^{o}C per day reaching thermophilic (55^{o}C) was found satisfactory.

- This study found that on increasing the loading rate, the biogas production decreased. The specific methane production rate of 278.4, 225.9 and 146.0 L CH_4/kg VS_{added} were found in loading rate 1 (2.5 kg VS/m^3.d), 2 (3.3 kg VS/m^3.d) and 3 (3.9 kg VS/m^3.d) respectively.

- Volatile solid reductions of 59.39 %, 54.39% and 39.53% were obtained during the loading rate 1, 2 and 3 respectively.

- The principal instability associated with loading rates 2 and 3 seem to be due to overloading of the system.

- The experimental results showed that the end products of anaerobic digestion are relatively stable. By analyzing the nutrient contents of the residues, it was clear that this digestate has a potential to be used as soil conditioner since nitrogen, phosphorus and potassium met with Thailand guideline developed by Land Development Department. Alternatively, calorific value of digestate was found 12.1 MJ/kg which has potential to be used as RDF if further mixing with industrial waste can be done.

- The energy production and consumption was done only in continuous loading rates. It showed that an energy surplus from this system obtained was 80%.

5.2 Recommendations

Anaerobic digestion option proves an attractive option to be used as the technology for treating organic fraction of MSW. It can offer the production of biogas as well as the potential economical value of residue byproducts. However, an attempt on the optimization of continuous process for this experiment was not completely achieved since the highest VS reduction obtained is only 59.21%. Therefore, the new concept should be envisioned that may possibly improve the process for further study. Thus, the following aspects can be taken as the recommendations for future study of such anaerobic digester;

- Source segregation of organic fraction of solid waste should be implemented in whole AIT community in order to have sustainable solid waste management.

- In this experiments, the nutrient contents of the organic wastes were not found in suitable range (C/N ratio = 20-30) for anaerobic digestion. Therefore, the different fractions of the organic wastes should be blended to achieve the optimum nutrient concentrations.

- For BMP test, design of the reactor should be modified to confirm complete air tight since the problem was faced on the reactor configuration while operating at thermophilic temperature (55^{o}C) for 50 days. Special rubber stopper should be used that can retain the specified temperature.

- Since the methane is the excellent indicator of greenhouse effects, it should be trapped and should be either used or disposed properly.

- The BMP test should be conducted to fresh digestate obtained from the experiments to assess the biodegradability.

- The percolate of the sludge drying bed should be further treated with Upflow Sludge Blanket Reactor (UASB) since the percolate and leachate obtained from digester still have high organic loadings.

- The design of sand drying bed should be modified to avoid clogging of the sand. Since the influent to this system is not like sludge, the use of sand is not necessary that cause the clogging problem. So it is suggested to use only graded gravel (smaller sized) at upper portion of the sludge drying bed.

- The AD system should be operated into two stages in order to get higher methane yield and to control the process effectively.

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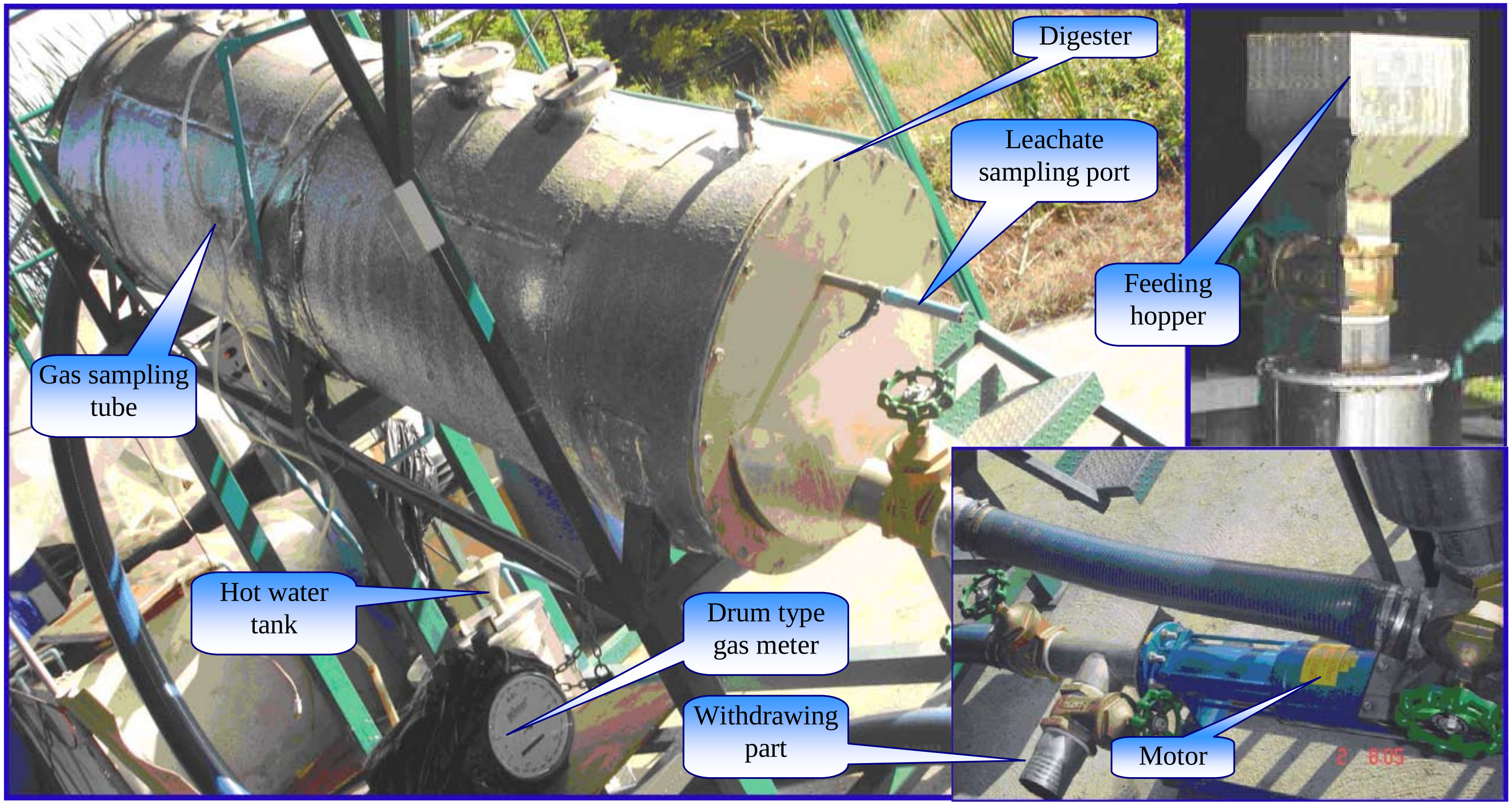
Appendices

Appendix A Photograph

Anaerobic digestion system



Appendix B Sample calculation

1. Moisture content, Total Solid (TS) and Volatile Solids (VS)

Weight of sample before drying = 950 g
Weight of sample after drying = 177.6g

$$\% \text{ MC} = \frac{(950 - 177.6)}{950} \times 100 = 81.30\ \%$$

$$\% \text{ TS} = 100 - 81.30 = 18.70\ \%$$

Weight of sample after 105 ^{o}C = 1.956 g
Weight of sample after 550 ^{o}C = 0.312 g

$$\% \text{ VS} = \frac{(1.956 - 0.312)}{1.956} \times 100 = 84.07\ \%$$

Total Wet Weight (WW) of sample = 218 kg
Dry Weight (DW) = (WW X % TS) = 218 kg x 0.18 = 40.74 kg
Volatile Weight = (DW X % VS) = 40.74 kg x 0.84 = 34.2 kg

2. Methane potential of MSW in lab-scale reactor

Step 1: Determination of mass of CH_4 in 0.2 mL sample

Standard curve for determination of CH_4 mass in sample
Mass of CH_4 (g) = Area (CH_4 peak in chromatograph) * K (constant)
K = $1.7759 * 10^{-10}$
Area_{38} (before removal) = 386226
Area_{38} (after removal) = 328493

Mass of CH_4 in sample:
Before removal = 386226 * 1.7759 * 10-10 = 68.590 µg
After removal = * $1.7759 * 10^{-10}$ = 58.337 µg

Step 2: Determination of CH_4 mass in reactor

Volume of headspace (V) = 2292 mL

Mass of CH_4 in reactor:

$$M_{38} \text{ (reactor)} = \frac{V * m(\text{sample})_{38}}{0.2}$$

$$M_{39} \text{ (reactor, before removal)} = \frac{V * m(\text{sample})_{38}}{0.2} = \frac{2292 * 68.590}{0.2}\ \mu g = 0.786 \text{ g}$$

$$M_{39}\text{ (reactor, after removal)} = \frac{V * m(\text{sample})_{38}}{0.2} = \frac{2292 * 58.337}{0.2}\ \mu g = 0.669\ g$$

Step 3: Determination of amount of removal

$$M_i(\text{removal}) = m_{38}(\text{before removal}) - m_{38}(\text{after removal})$$

$$M_{39}(\text{removal}) = 0.786 - 0.669 = 0.117\ g$$

Step 4: determination of cumulative mass production

Cumulative methane = 2.373 + 0.117 = 2.49 g

Step 5: Determination of biogas production (in STP)

Universal gas equation:

$$PV = \frac{m}{M} * RT$$

P: standard pressure (1 atm)
V: CH_4 production (L in STP)
M: mass of CH_4
M: molecular weight of CH_4
R: universal gas constant = $8.2057*10^{-2}$ ($L.atm.mol^{-1}.K^{-1}$)
T: standard temperature($25^oC = 298\ ^oK$)

$$V = \frac{m * RT}{MP} = \frac{2.491 * 8.2057*10^{-2} * 298}{16 * 1} = 3806.072\ NmL$$

3. Calculation of methane potential

$$\text{Methane potential (NmL)} = \frac{\text{Methane production(sample)} - \text{Methane production(blank)}}{\text{Kg VS in reactor}}$$

$$= \frac{(4990.26-1586.819)}{(116.1 * 0.1273 * 0.7194)}\ ml/g\ VS$$

$$= 320.1\ L\ CH_4/\ kg\ VS$$

4. Calculation of energy balance for loading rate 1

4.1 Energy used

- **Mechanical energy requirements**

Total amount of waste fed (m) = 218 kg

Energy required for shredding (E_S) $= \frac{0.5 \text{ L (gasoline)}}{100 \text{ kg (feedstock)}} * m$

$= \frac{0.5 * 218}{100}$

$= 1.09$ L

Since, 1 gallon of gasoline = 110,250 BTU
= 110,250 BTU * 1.0551 [1.0551: conversion factor]
= 116,324.8 KJ/gal x (1 gal/3.785 L) x 1..09 L
= 33,499.25 KJ = 33.50 MJ

Operation of pump = 5 min/d
Total hour of operation = 5 min/day* 25 day = 125 min = 2 h

Energy required for feeding (E_F) = P * T
= 1.5 kW * 2 h
= 3 KWh x (3600 kJ/1 KWh)
= 10,800 kJ = 10.8 MJ

- **Calorific energy requirements**

E_H = m * C_p (T_i-T_o)
= 218 kg * 4.185 kJ/kg.^{o}C * (55-29)
= 23,720 kJ = 23.720 MJ

- **Energy production**

Total biogas production = 15890.4 L
Methane content (60%) = 9534.24 L

E_A = (M_P) * (L.H.V. of methane)
= 9534.24 L * 35.8 kJ/L {L.H.V of methane = 35.8 kJ/L; Bouallagui et al., 2004}
= 341325 kJ = 341.32 MJ

- **Net energy production**

E_P = E_A - E_S – E_F – E_H
= (341.32 – 33.50 – 10.8 – 23.720) MJ
= 273.3 MJ
= 1.25 MJ/kg fresh waste

5. Example of mass balance

- **Characteristics of input feedstock**

Total feedstock wet weight	= 9
Moisture content	= 81.31 %
Volatile solids	= 84.07 %
Total moisture	= 7.32 kg
Total dry solids	= 1.68 kg

Volatile solids present in the waste = 1.41 kg

- **Characteristics of fresh digestate**

Total solids in the leachate	= 27 g/L
Volatile solids in leachate	= 12 g/L
Moisture content of digestate	= 75 %
Volatile solids present in the digestate	= 60 %
Total digestate to be withdrawn	= X
Total leachate to be withdrawn	= Y

- **Water mass balance**

7.318 = 0.75 X + 0.973 Y Eq. (1)

- **Volatile solids loss in the biogas production**

With daily biogas production of 635 L (50% CH_4 and 50% CO_2), volatile solid loss in biogas production (kg) is calculated as follow:

{635 x [16 x (50/100) + 44 x (50/100)]/22.413} = 0.850 kg

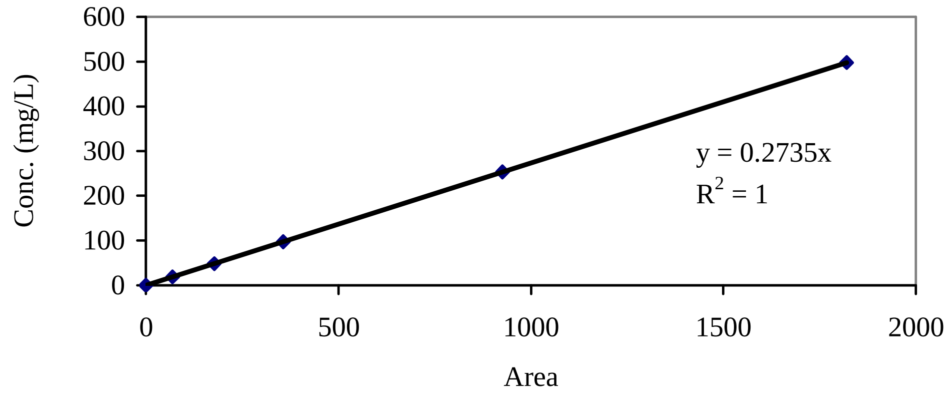
- **Volatile solids intake = Volatile solids out**

1.41 = (0.25 x 0.75) X + (12/1000) Y + 0.850 Eq. (2)

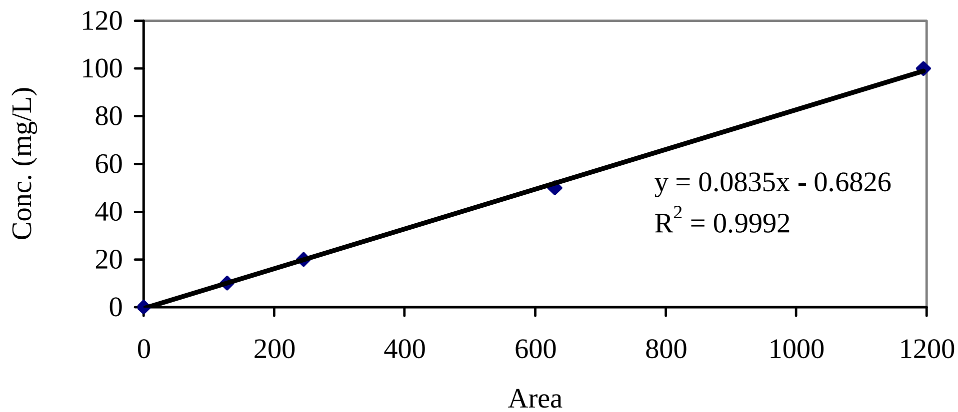
So, X = 3.4 kg
Y = 5.6 kg

Appendix C   TC and IC standard curves

TC Standard curve



IC Standard curve



Appendix D Pilot scale-continuous anaerobic digestion

Table D -1 Biogas production during start-up period

Run time (days)	Daily biogas production (L)	Cumulative biogas production (L)	Biogas	
			$\%CH_4$	$\%CO_2$
0	0	2.6		95.00
1	827.40	830.0		93.00
2	840.00	1670.0		92.93
3	850.00	2440.0		92.91
4	855.60	3295.6		92.50
5	799.80	4095.4	7.29	92.71
6	365.60	4461.0	17.92	82.08
7	262.50	4723.5	27.34	72.66
8	206.50	4930.0	43.25	56.75
9	316.10	5246.1	54.73	45.27
10	179.20	5425.3	59.95	40.05
11	113.80	5539.1	60.97	39.03
12	105.90	5586.0	60.73	39.27
13	90.60	5676.6	60.19	39.81
14	68.00	5744.6	59.85	40.15
15	76.10	5820.7	58.49	41.51
16	101.40	5922.1	57.64	42.36
17	74.90	5997.0	57.91	42.09
18	85.00	6082.0	57.43	42.57
19	20.70	6102.7	57.88	42.12
20	37.90	6140.6	58.18	41.82
21	26.50	6167.1	55.21	44.79
22	50.20	6217.3	58.21	41.79
23	192.90	6410.2	54.81	45.19
24	223.30	6633.5	53.76	46.24
25	223.10	6856.6	53.57	46.43
26	350.00	7206.6	53.17	46.83
27	300.20	7506.8	52.94	47.06
28	191.60	7698.4	54.71	45.29
29	379.30	8077.7	54.31	45.69
30	370.70	8448.4	55.53	44.47
31	428.20	8876.6	57.71	42.29
32	431.20	9307.8	59.77	40.23
33	532.20	9840.0	60.80	39.20
34	513.40	10353.4	63.56	36.44
35	504.10	10857.5	63.56	36.44
36	617.90	11475.4	63.86	36.14

Run time (days)	Daily biogas production (L)	Cumulative biogas production (L)	Biogas	
			%CH_4	%CO_2
37	766.40	12241.8	65.20	34.80
38	791.90	13033.7	66.68	33.32
39	776.90	13810.6	65.96	34.04
40	696.30	14506.9	66.52	33.48
41	547.30	15054.2	65.02	34.98
42	453.30	15507.5	64.30	35.70
43	426.00	15933.5	63.38	36.62
44	387.80	16321.3	63.36	36.64
45	349.00	16670.3	62.51	37.49
46	346.20	17016.5	62.44	37.56
47	331.60	17348.1	62.50	37.50
48	346.00	17694.1	62.74	37.26
49	319.20	18013.3	63.09	36.91
50	311.20	18324.5	64.07	35.93
51	317.80	18642.3	64.58	35.42
52	318.20	18960.5	65.32	34.68
53	300.20	19260.7	65.55	34.45
54	283.80	19544.5	66.57	33.03
55	266.30	19810.8	66.49	33.11
56	231.70	20042.5	66.56	33.04

Table D-2 Leachate Characteristics during start-up

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)
1	5.44	1175			52800		4200.0
2	6.45	1270	2434.62	25810		980	5040.0
3	7.02	1440	2951.03	22490	70400	1260	4200.0
4	6.86	1620	2670.19	24080		1540	5320.0
5	6.48	1605	3250.80	28620		1960	4480.0
6	6.56	1635	3267.96	29150		2380	3920.0
7	6.67	1710	3253.42	27880	35200	2100	4760.0
8	6.58	1730	3094.82	24880		2492	3640.0
9	6.77	1590	2763.49	25370		2240	3920.0
10	6.76	1400	3098.31	23330		2100	3640.0
11	7.30	1640	2811.18	25500	38720	1960	2240.0
12	7.40	1040	2914.38	13520		1540	3360.0
13	7.12	1210	3121.48	16060		1540	3080.0
14	7.01	1555	2540.47	20700		1960	3360.0
15	6.98	1725	3161.81	22800	35200	2380	4760.0
16	7.05	1620	2612.81	25210		2520	4208.4
17	7.01	1735	3147.36	25600		2100	3935.7
18	7.20	1755	3176.34	24900		2240	3920.0
19	7.30	1840	2831.66	24890	28160	2380	3640.0
20	6.98	1710	3802.61	22150		2940	3360.0
21	7.04	1770	3170.20	22720		2520	3920.0
22	7.40	1810	3027.21	24210		2800	3360.0
23	7.01	1725	3518.66	23400	31680	2660	3920.0
24	6.96	1745	2904.47	22270		2940	3360.0
25	7.03	1815	2366.38	23660		2800	3920.0
26	7.20	1795	4043.43	22770		2660	3647.3
27	7.30	1815	3562.53	22400	28160	2940	4200.0
28	7.40	1875	3537.20	23380		3080	3927.8
29	7.20	1845	2952.20	21149		2660	3360.0
30	7.59	1965	3489.96	20340		2520	3086.2
31	7.57	1710	3252.11	20560	31680	2380	3373.4
32	7.68	1855	2876.45	20380		2702	3661.8
33	7.76	2200	2635.46	20320		2688	3951.4
34	7.92	1855	2546.18	19650		2716	3393.6
35	7.94	1985	2614.27	19510		2758	3117.0
36	7.84	2055	2678.59	18900	30976	2800	3407.0
37	7.83	2080	2719.55	18280		2800	2844.8
38	7.80	1815	2896.77	17590		2660	3420.5
39	8.08	2115	2876.58	16780		2660	3712.8
40	8.16	2045	2347.11	16410	31680	2660	4006.2
41	8.17	2250	2995.75	17170		2800	3440.6
42	8.02	1820	2623.48	16310		2660	3734.6
43	8.12	1895	2806.12	15730		2940	4317.6

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)
44	8.17	2010	2700.00	15590	28160	2800	4037.6
45	8.19	2325	2110.12	16400		3220	3756.5
46	8.11	2000	2431.12	17140		3360	4342.8
47	8.12	1880	2035.24	16140		2660	3481.0
48	8.06	2000	1867.98	15900	17600	2940	4069.0
49	8.15	2060	2503.60	16360		2800	4368.0
50	8.22	2065	2242.84	15000		2660	4480.0
51	8.20	1970	2125.17	14500		2800	3920.0
52	7.97	1975	2237.37	14900	17600	2940	4200.0
53	8.34	2235	2523.34	14300		2660	3640.0
54	8.33	2185	1383.40	14700		2800	4480.0
55	8.21	2325	1370.18	14600		3220	3920.0
56	8.39	2400	1312.01	14300	15488	2800	3360.0

Table D-3 Biogas production during continuous loadings

Run time (days)	Daily biogas production (L)	Cumulative biogas production (L)	Biogas	
			%CH_4	%CO_2
Loading 1				
57	264.60	20307.1	44.6	55.4
58	412.50	20719.6	53.2	46.8
59	662.90	21382.5	65.3	34.7
60	640.60	22023.1	65.5	34.5
61	437.20	22460.3	54.9	45.1
62	629.20	23089.5	59.4	40.6
63	610.00	23699.5	56.9	43.1
64	630.60	24330.1	67.4	32.6
65	530.30	24860.4	65.2	34.8
66	572.00	25432.4	62.3	37.7
67	813.40	26245.8	62.3	37.7
68	798.30	27044.1	58.6	41.4
69	785.90	27830.0		
70	787.70	28617.7		
71	746.00	29363.7		
72	897.80	30261.5		
73	955.10	31216.6		
74	1019.00	32235.6		
75	847.00	33082.6		
76	1341.30	34423.9		
77	854.20	35278.1		
78	1113.60	36391.7		
79	847.10	37238.8		
80	1091.40	38330.2		
81	1211.90	39542.1	62.0	38.0
Loading 2				
82	1395.00	40937.1		
83	1138.10	42075.2		
84	587.90	42663.1		
85	952.50	43615.6		
86	546.20	44161.8		
87	661.90	44823.7		
88	706.60	45530.3		
89	556.90	46087.2		
90	402.50	46489.7		
91	434.90	46924.6	53.6	46.4
92	562.30	47486.9	51.9	48.1
93	675.00	47613.7	59.0	41.0

Run time (days)	Daily biogas production (L)	Cumulative biogas production (L)	Biogas	
			%CH_4	%CO_2
94	687.60	48301.3	63.7	36.3
95	815.80	49117.1	55.8	44.2
96	782.90	49900.0	59.4	40.6
97	479.00	50379.0	50.0	50.0
98	607.50	50986.5	54.8	45.2
99	633.70	51620.2	46.1	53.9
100	665.30	52285.5	56.4	43.6
101	845.80	53131.3	42.5	57.5
102	883.20	54014.5	52.9	47.1
103	870.60	54885.1	44.0	56.0
104	900.10	55785.2	55.7	44.3
105	1000.20	56785.4	51.3	48.7
106	763.40	57548.8	50.9	49.1
Loading 3				
107	682.50	74120.2	31.5	68.5
108	631.00	74751.2	43.1	56.9
109	729.70	75480.9	47.6	52.4
110	638.80	76119.7	37.9	62.1
111	862.80	76982.5	47.0	53.0
112	692.90	77675.4	44.2	55.8
113	853.20	78528.6	46.0	54.0
114	503.70	79032.3	47.9	52.1
115	815.90	79848.2	51.3	48.7
116	542.40	80390.6	49.4	50.6
117	670.50	81061.1	43.2	56.8
118	540.40	81601.5	51.7	48.3
119	556.20	82157.7	52.8	47.2
120	733.80	82891.5	46.0	54.0
121	655.40	83546.9		
122	830.60	84377.5	50.6	49.4
123	764.70	85142.2	46.9	53.1
124	455.00	85597.2	53.1	46.9
125	717.90	86315.1	50.3	49.7
126	1077.10	87392.2		
127	399.40	87791.6	50.5	49.5
128	908.20	88699.8	48.0	52.0
129	599.20	89299.0	49.4	50.6
130	505.40	89804.4	46.7	53.3
131	809.60	90614.0	50.6	49.4

Table D-4 Leachate Characteristics during continuous loading

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	DOC (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)
Loading 1						
57	7.5	2600	22760	98440	3220	4760
58	7.6	2600	23270	94160	3360	4760
59	7.7	2800	22780	94160	3615	4760
60	8.0	3000	21330	89880	3780	5320
61	8.0	3200	21910	89880	3780	5600
62	8.0	3000	22990	64200	3640	5320
63	7.9	3200	21330	55640	3920	5600
64	8.0	2900	19890	47080	3500	4760
65	8.0	3120	20590	51360	3640	5040
66	8.0	3000	19320	42800	3780	4760
67	8.0	3200	19320	42800	3640	5880
68	8.0	3000	17388	38520	4060	5880
69	7.9	2900	21252	47080	3920	5852
70	7.9	3200	19320	42800	3640	5768
71	8.0	3000	21252	47080	3920	5488
72	7.9	3200	19320	42800	3780	5572
73	7.9	3000	15456	34240	2800	5600
74	8.0	2800	15456	34240	3080	5824
75	8.0	3200	17388	38520	3080	5880
76	7.9	3000	23184	51360	2240	4480
77	7.9	3400	15456	34240	2100	4200
78	7.9	3200	13524	29960	2660	5320
79	7.9	3200	15456	34240	2800	5600
80	7.9	3400	11592	25680	2520	4480
81	8.0	3200	11978	26536	2520	5040
Loading 2						
82	8.0	2255	14690	49280	2520	2800
83	7.7	2115	15830		2940	3920
84	7.5	2200	16070		2800	3360
85	7.4	2105	14960		2940	3640
86	7.4	2200	17430	52800	2940	3360
87	7.4	2000	18150		2520	3920
88	7.5	2200	19500		2800	4200
89	7.4	2800	19640	52800	2940	4200
90	7.4	2400	18670	49280	3220	4480
91	7.5	1800	19580	45760	2940	3360
92	7.5	2000	18755	49280	3360	3640
93	7.6	2000	18510	45760	3360	3920

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	DOC (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)
94	7.6	2200	17310	42240	3080	4200
95	7.7	2600	18345	49280	3080	3640
96	7.8	2200	20660	42240	3080	4200
97	7.7	2400	18405	38720	2940	4480
98	7.7	2400	16575	38720	3080	4760
99	7.5	2800	17865	52800	2380	4480
100	7.6	2000	17465	49280	3080	3640
101	7.3	2600	19435	66880	2520	4200
102	7.0	2200	21700	59840	3640	4480
103	7.0	2400	20145	63360	3080	4480
104	7.1	2800	20850	80960	3220	4480
105	7.1	2400	25010	63360	3360	4760
106	6.6	2200	22200	77440	3220	4760
Loading 3						
107	6.6	2200	20315	56320	3360	4200
108	6.5	2000	23025	63360	3360	5320
109	6.7	2200	23635	59840	3080	4760
110	6.5	2200	24260	77440	3500	4480
111	6.6	1800	23730	70400	3220	4480
112	6.6	2200	24970	80960	3640	5040
113	6.8	2400	25620	77440	3780	5880
114	6.7	2200	24790	70400	3220	5040
115	6.5	2400	30090	73920	2940	5600
116	6.6	2200	27300	80960	2520	5320
117	6.6	2400	24470	56320	3080	5320
118	6.5	2240	24910	49280	2660	5040
119	6.8	2260	26450	80960	2940	5040
120	6.5	2400	27420	66880	3220	4760
121	6.5	2200	27450	70400	3220	4760
122	6.5	2400	26760	95040	2940	4760
123	6.4	2260	30320	80960	3640	5600
124	6.5	2300	31270	88000	3080	5320
125	6.8	2220	29290	84480	2940	5320
126	6.7	2280	29490	91520	2940	5600
127	6.7	2340	29050	88000	2800	4200
128	6.7	2300	28660	84480	2380	3640
129	6.8	2260	28090	66880	3080	4200
130	6.8	2220	26900	70400	2800	4480
131	7.0	2240	26210	70400	2940	3920

Appendix E Solid waste characteristics of fresh and digested waste

Parameters	Units	Fresh waste	Digestate
Total wet weight	kg	218	
Moisture content (MC)	%	81.30	
Total Solids (TS)	%	18.70	
Volatile Solids (VS)	% TS	84.07	
Total Volatile Solids (TVS)	kg	34.2	
VS reduction			
Loading 1	%	59.21	
Loading 2	%	54.39	
Loading 3	%	39.53	
Nutrient analysis			
N	%	2.06	1.20
P	%	0.15	0.45
K	%	0.13	0.40
C	%	43.59	22.15
C/N		21.15	18.46
Calorific value	MJ/kg	14.3	12.1

Appendix F Solid waste generation

Date	Cafeteria				Snacks bar	Households
	Vendor A	Vendor B	Vendor C	Vendor D		
25-Oct-07	12	11	8	9	17	6
10-Nov-07	14	13	7	7	18	7
24-Nov-07	13	12	9	6	20	4
10-Dec-07	13	10	10	8	22	6
24-Dec-07	12	13	7	9	18	7
10-Jan-08	11	12	8	10	19	9
24-Jan-08	13	11	9	7	20	8
10-Feb-08	12	12	8	6	21	7
24-Feb-08	13	11	7	9	24	9

Appendix G Sample calculation for post treatment

Total amount of fresh digestate = 82 kg

Characteristics of wastes

- TS (fresh digestate) = 25%
- TS (dewatered digestate) = 50%
- TS (percolate) = 2%

Total solids in fresh digestate = 82 * 0.25
= 20.5 kg

Total amount of dewatered digestate = X
Total amount of percolate = Y

We have, X + Y = 82 Eq. (1)

Total solids in = Total solids out

or, 20.5 = 0.50 *X + 0.02 * Y Eq. (2)

Thus, X = 39 kg
Y = 43 kg

$$\text{Weight reduction} = \frac{(82 - 39)}{82} * 100 = 52.4\ \%$$

Appendix H Sample calculation for conceptual AD plant

- **Design of AD plant**

Total amount of daily waste generation = 1900 kg/d
Total daily organic wastes = 1140 kg/d (60% of total waste amount)
Organic loading rate = 2.5 kg VS/m^3.d (optimum loading rate as obtained from pilot scale experiment)
Characteristics of the wastes, TS = 18 % and VS = 84 %
Total daily volatile solids = 172 kg VS/d

Total volume of reactor required = 172 kg VS/d/ (2.5 kg VS/m^3.d)
= 68.8 m^3

The required volume of reactor can be managed by providing 4 reactors of 18 m^3 each.

Thus, the size of each reactor = 3 m (diameter) x 2.5 m (height)
Daily feedstock per reactor = 1140 kg/4 = 285 kg/d

- **Energy potential**

Specific methane production = 278.4 L CH_4/kgVS (obtained from pilot scale experiments)

Total methane production from actual plant = 278.4 L CH_4/kg VS * 172 kg VS
= 47884.8 L CH_4

Total energy production = 47884.8 L CH4 * 35.8 MJ/L
{Calorific value of CH_4 = 35.8 MJ/L; Bouallagui et al., 2004}
= 1714,275.84 MJ

Total surplus energy = 1714275.84 * 0.80
{Surplus energy =80% as obtained in pilot scale experiment}
= 1371420.67 MJ
= 1371.42 GJ

From the experiments in dewatering process, 0.48 kg dewatered digestate per kg fresh digestate was obtained.

Total dewatered digestate = 1140 kg * 0.48
= 547 kg dewatered digestate

Total energy production from dewatered digestate if subjected for RDF energy;
= 547kg * 12.1 MJ/kg DW =6618.7 MJ

- **Calculation of greenhouse gases reductions**

Amount of Methane production from landfills = 140 L CH_4/kg organic waste
(Source: Bonger and Spokas, 1993)
Total amount of methane reduction from this system = 140 L/kg * 1140 kg
= 159600 L CH_4 = 159.6 m^3 CH_4

Appendix I Daily feedstock input and withdrawal during continuous loadings

Description	total wet weight input (kg/d)	Total water (kg)	Digestate to be withdrawn (kg/d)	Moisture content (%)	VS in digestate (kg/d)	Water in digestate (kg/d)	VS in leachate (kg)	Daily biogas production (L)	VS loss in biogas (kg)	leachate to be withdrawn (kg)
Loading 1	9	7.3	3.4	75	0.50	0.134	0.068	635	0.850	5.6
Loading 2	13.5	11	4.1	75	0.64	0.302	0.159	780	1.044	9.4
Loading 3	12	9	7.3	75	1.17	0.288	0.011	670	0.897	4.7

Appendix J BMP data in lab scale

Sample no.	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)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
OFMSW											
1	1	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	2	6457	6457	1.147	1.147	0.013	0.013	0.000	0.000	0.000	0.000
3	3	15645	15324	2.778	2.721	0.032	0.031	0.001	0.001	0.001	0.998
4	4	203100	172514	36.069	30.637	0.413	0.351	0.062	0.063	0.063	96.125
5	5	260293	226346	46.225	40.197	0.530	0.461	0.069	0.132	0.132	201.704
6	6	331672	287833	58.902	51.116	0.675	0.586	0.089	0.221	0.221	338.049
7	7	332707	281041	59.085	49.910	0.677	0.572	0.105	0.326	0.326	498.737
8	8	334506	326745	59.405	58.027	0.681	0.665	0.016	0.342	0.342	522.874
9	9	326786	286543	58.034	50.887	0.665	0.583	0.082	0.424	0.424	648.035
10	11	273771	181390	48.619	32.213	0.557	0.369	0.188	0.795	0.795	1215.574
11	13	339125	286276	60.225	50.840	0.690	0.583	0.108	0.944	0.944	1441.990
12	15	301906	288185	53.615	51.179	0.614	0.587	0.028	1.104	1.104	1687.761
13	17	313259	293034	55.632	52.040	0.638	0.596	0.041	1.146	1.146	1750.665
14	19	331176	331176	58.814	58.814	0.674	0.674	0.000	1.184	1.184	1808.605
15	21	332428	298103	59.036	52.940	0.677	0.607	0.070	1.346	1.346	2057.454
16	23	340680	338895	60.501	60.184	0.693	0.690	0.004	1.417	1.417	2165.719
17	25	348244	308756	61.845	54.832	0.709	0.628	0.080	1.498	1.498	2288.690
18	28	340590	309988	60.485	55.051	0.693	0.631	0.062	1.678	1.678	2564.460
19	31	335179	305788	59.524	54.305	0.682	0.622	0.060	1.939	1.939	2963.714
20	34	376136	336745	66.798	59.803	0.766	0.685	0.080	2.198	2.198	3359.040

Sample no.	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)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
21	38	386226	328493	68.590	58.337	0.786	0.669	0.117	2.491	2.491	3806.072
22	42	395304	328573	70.202	58.351	0.805	0.669	0.136	3.045	3.045	4653.223
23	47	373927	373927	66.406	66.406	0.761	0.761	0.000	3.265	3.265	4990.255
24	50	373927	373927	66.406	66.406	0.761	0.761	0.000	3.265	3.265	4990.255
Blank											
1	1	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	2	26353	26353	4.680	4.680	0.053	0.053	0.000	0.000	0.000	0.000
3	3	30317	30317	5.384	5.384	0.061	0.061	0.000	0.000	0.000	0.000
4	4	37710	31447	6.697	5.585	0.076	0.064	0.013	0.013	0.013	19.411
5	5	48293	44532	8.576	7.908	0.098	0.090	0.008	0.020	0.020	31.067
6	6	75962	75915	13.490	13.482	0.154	0.154	0.000	0.020	0.020	31.213
7	7	93461	75915	16.598	13.482	0.190	0.154	0.036	0.056	0.056	85.593
8	8	109059	93494	19.368	16.604	0.221	0.190	0.032	0.088	0.088	133.833
9	9	117635	101358	20.891	18.000	0.239	0.206	0.033	0.121	0.121	184.282
10	11	130425	114755	23.162	20.379	0.265	0.233	0.032	0.178	0.178	272.174
11	13	138952	138952	24.676	24.676	0.282	0.282	0.000	0.209	0.209	319.003
12	15	147623	135462	26.216	24.057	0.299	0.275	0.025	0.252	0.252	385.757
13	17	143627	143819	25.507	25.541	0.291	0.292	0.000	0.252	0.252	385.163
14	19	159522	159522	28.330	28.330	0.324	0.324	0.000	0.252	0.252	385.133
15	21	169837	157926	30.161	28.046	0.344	0.320	0.024	0.302	0.302	461.447
16	23	176822	164000	31.402	29.125	0.359	0.333	0.026	0.354	0.354	540.840
17	25	183728	169567	32.628	30.113	0.373	0.344	0.029	0.417	0.417	637.447
18	28	186765	171400	33.168	30.439	0.379	0.348	0.031	0.499	0.499	763.266

Sample no.	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)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
19	31	205458	183877	36.487	32.655	0.417	0.373	0.044	0.595	0.595	909.444
20	34	209362	190096	37.181	33.759	0.425	0.386	0.039	0.716	0.716	1094.398
21	38	213746	197522	37.959	35.078	0.433	0.401	0.033	0.824	0.824	1259.877
22	42	213746	204204	37.959	36.265	0.433	0.414	0.019	0.932	0.932	1424.932
23	47	230476	221713	40.930	39.374	0.467	0.450	0.018	1.056	1.056	1613.978
24	50	230476	230476	40.930	40.930	0.467	0.467	0.000	1.056	1.056	1613.978

Dry Continuous Anaerobic Digestion of Municipal Solid Waste in Thermophilic Conditions

Binod Kumar Chaudhary

Examination committee:

Prof. C. Visvanathan (Chairperson)
Prof. Chongrak Polprasert
Dr. Chart Chiemchaisri

5 May, 2008

Presentation Outlines

1 Background

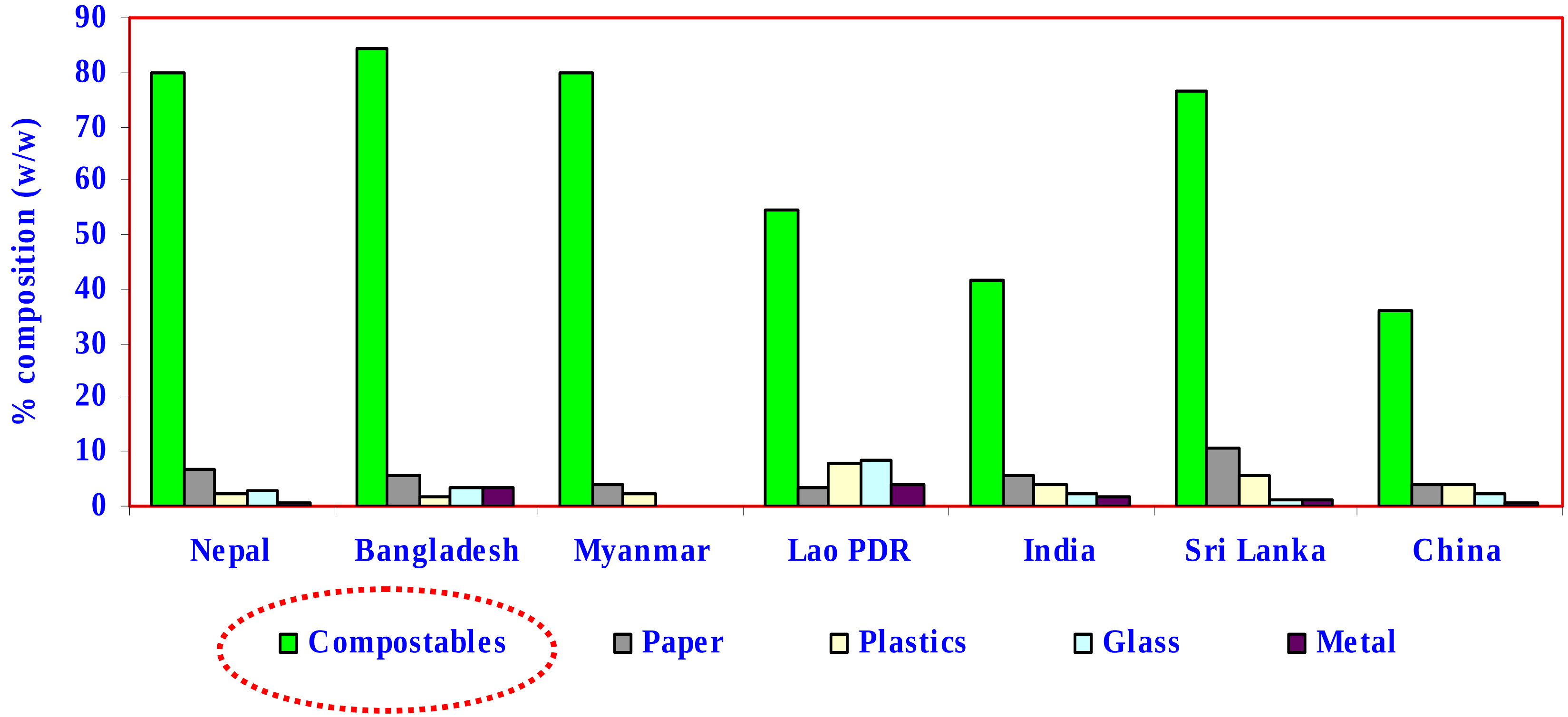
2 Objectives

3 Methodology

4 Results and Discussions

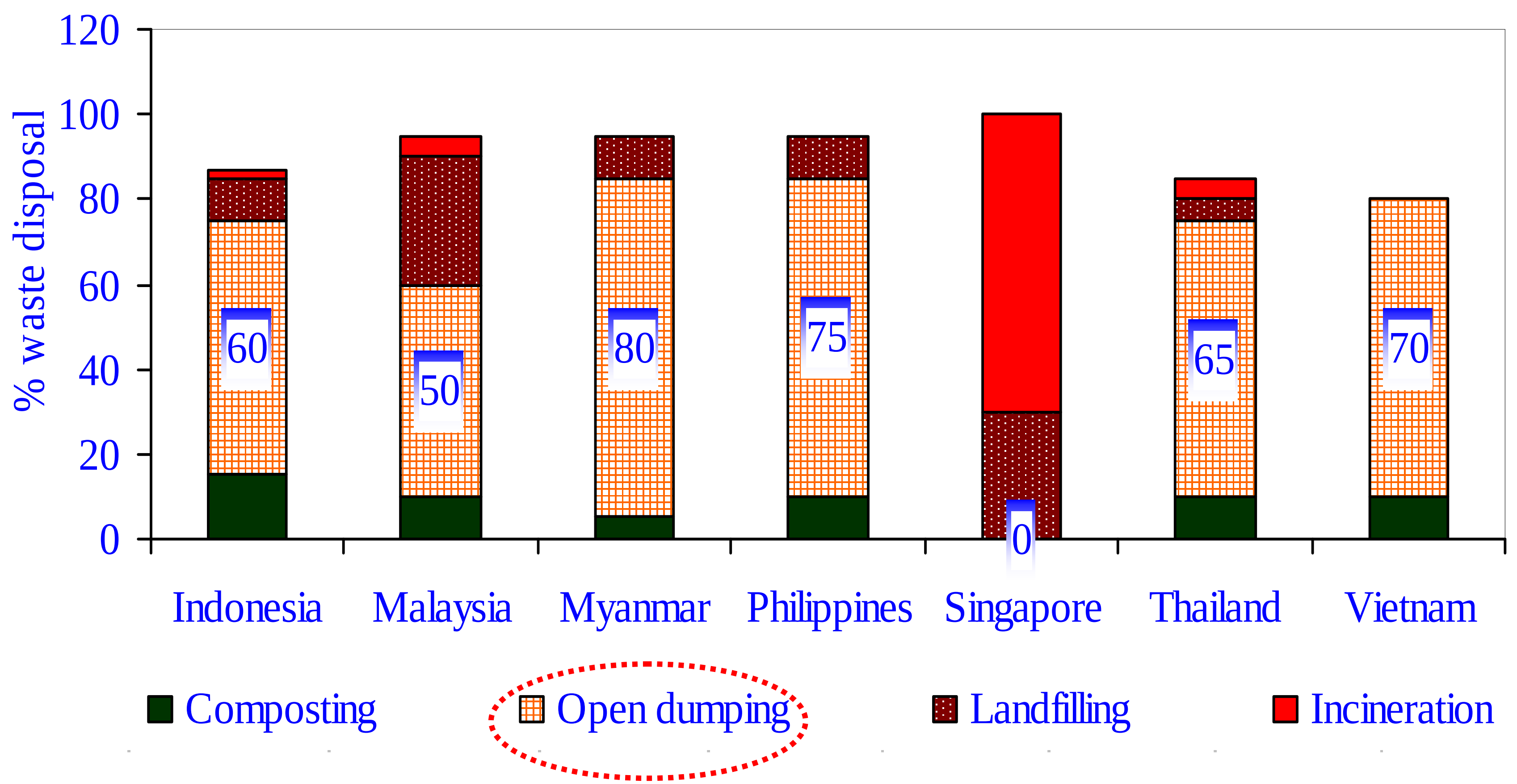
3 Conclusions and Recommendations

Waste Composition in Asian Countries



Source: Mendes & Imura, 2004

Waste Disposal



Source: UNEP, 2004

Problems Associated with Landfills

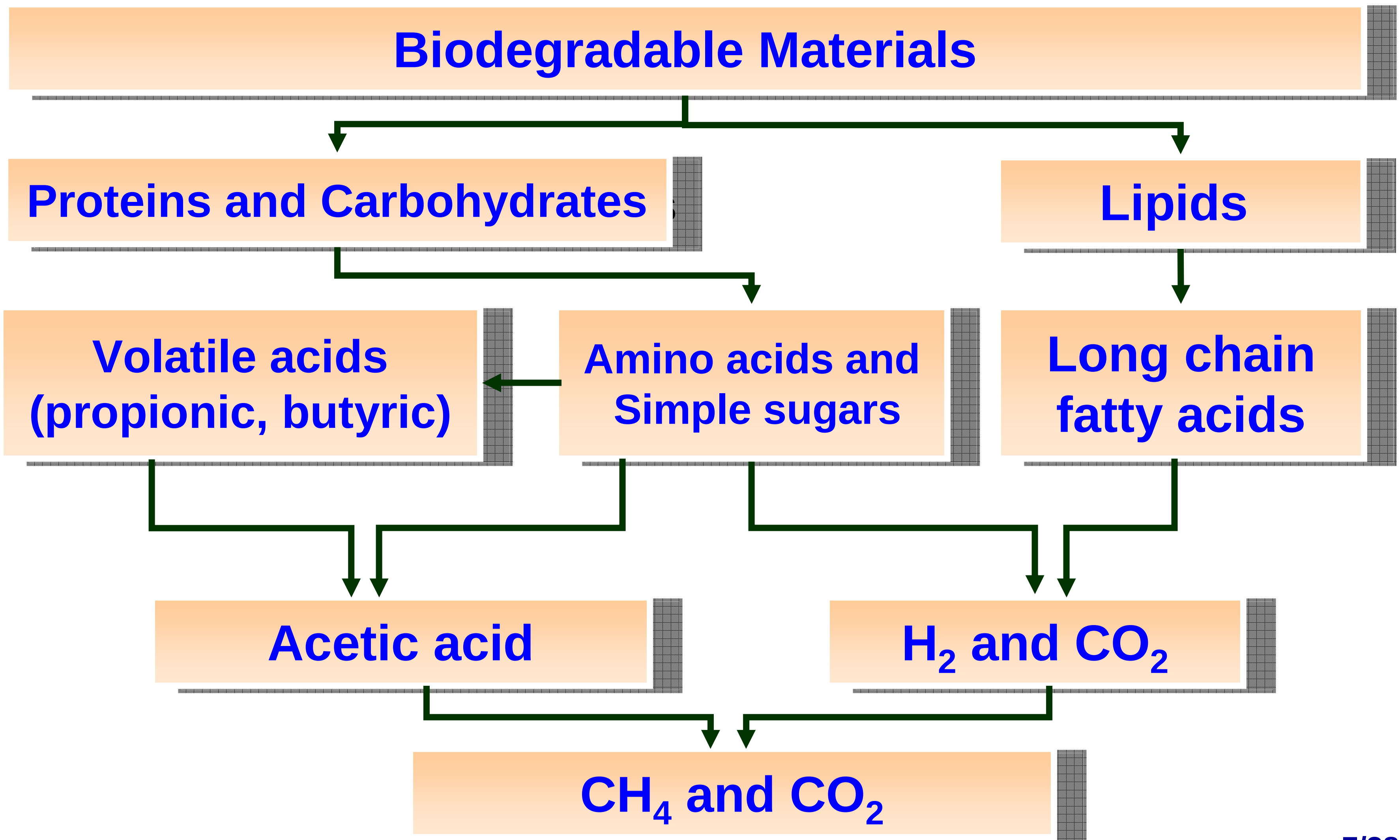
- Need for a site
- Risk of land and water pollution
- Noise pollution, visual pollution and the attraction of vermin
- Contribution to global warming
- Increased demand on natural resources and energy
- Economically expensive

AD as a pretreatment will be better solution for OFMSW

What is Anaerobic Digestion?

- A complex biological process involving the breakdown of organic matter by bacteria in the absence of air
- This process can be harnessed in an AD facility to produce:
  - Biogas
  - Solid fibrous material
  - Liquor
- Stable process achieving odor, pathogen and mass reduction
- Contributes to climate change objectives

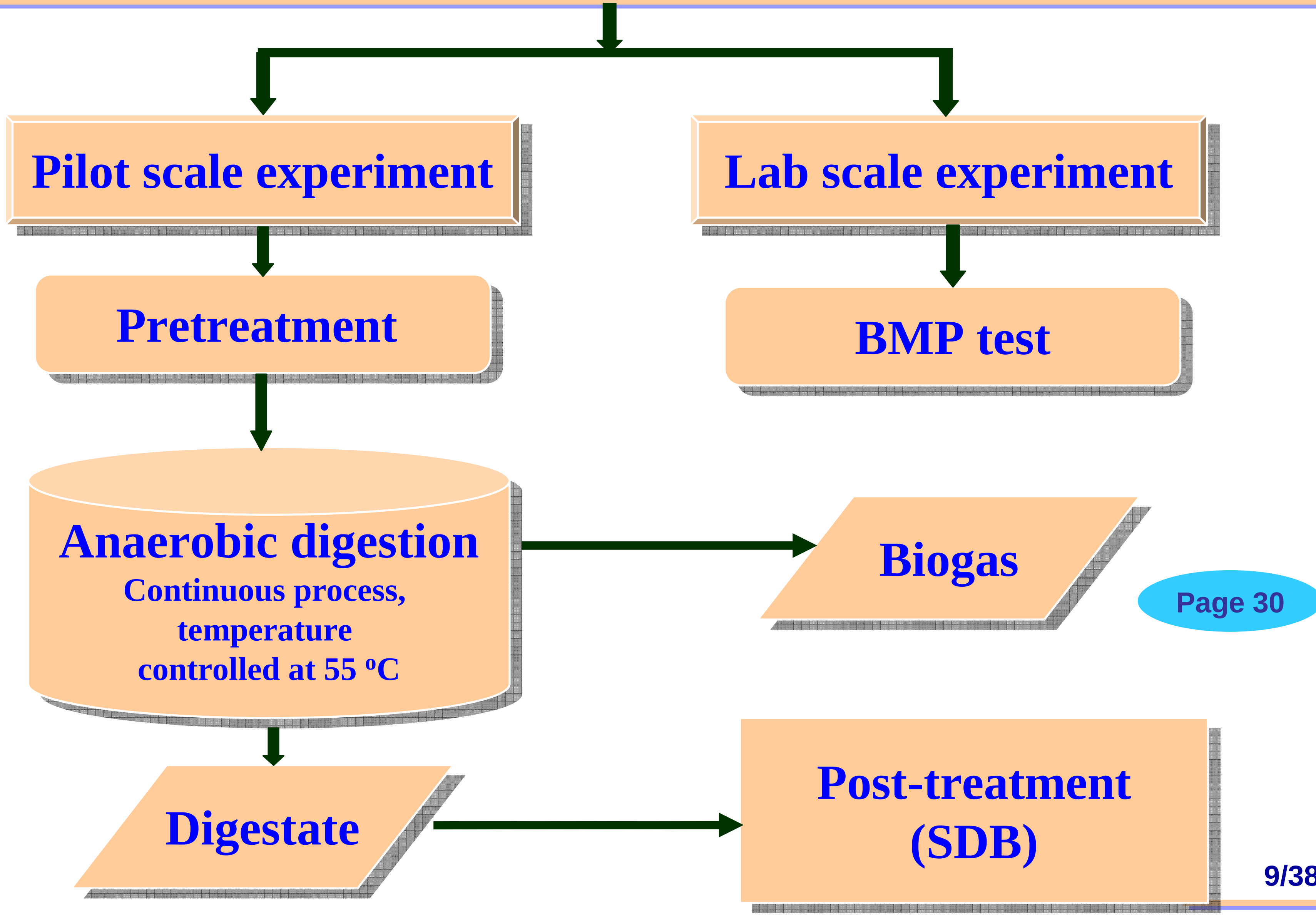
AD Process Fundamentals



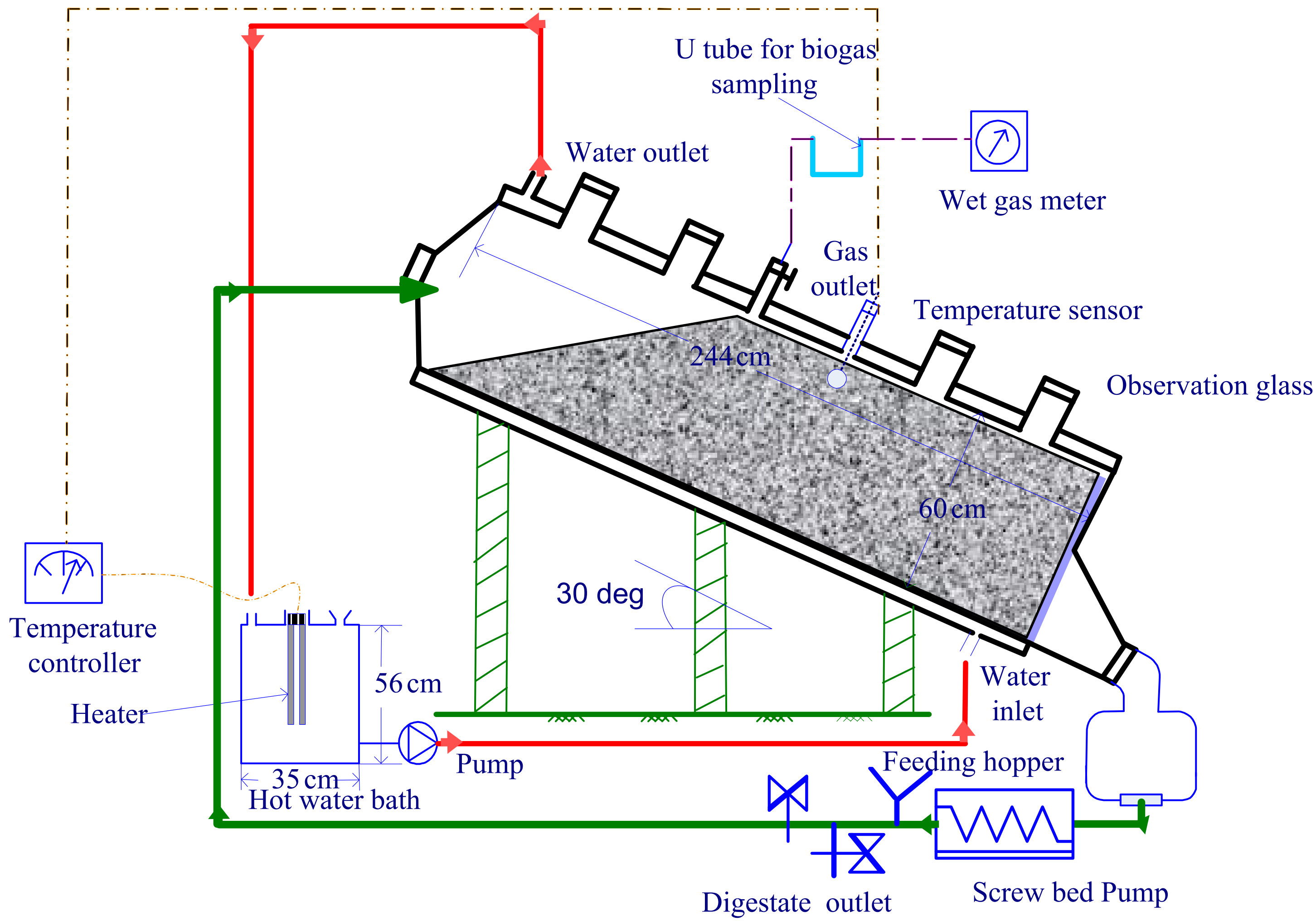
Objectives of this Study

- To optimize the methane yield of OFMSW with different organic loading rates in thermophilic conditions
- To analyze the operational parameters for the stability of dry continuous anaerobic digestion system
- To investigate the mass and energy balance in AD system
- To analyze the biodegradability of organic material by BMP test

Methodology



Experimental set-up



Page 31

Experimental set-up (Con't)

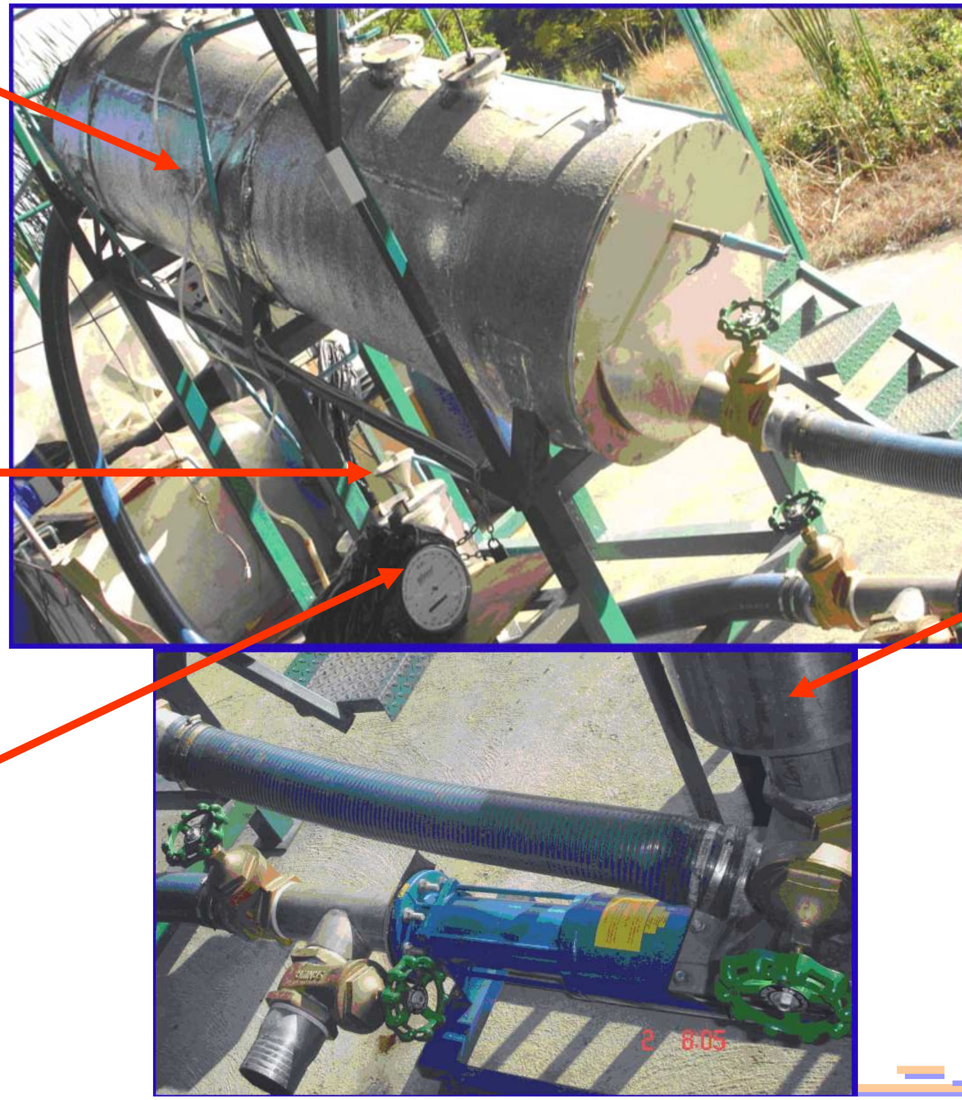
Experimental set-up (Con't)

Sampling tube

Hot water tank

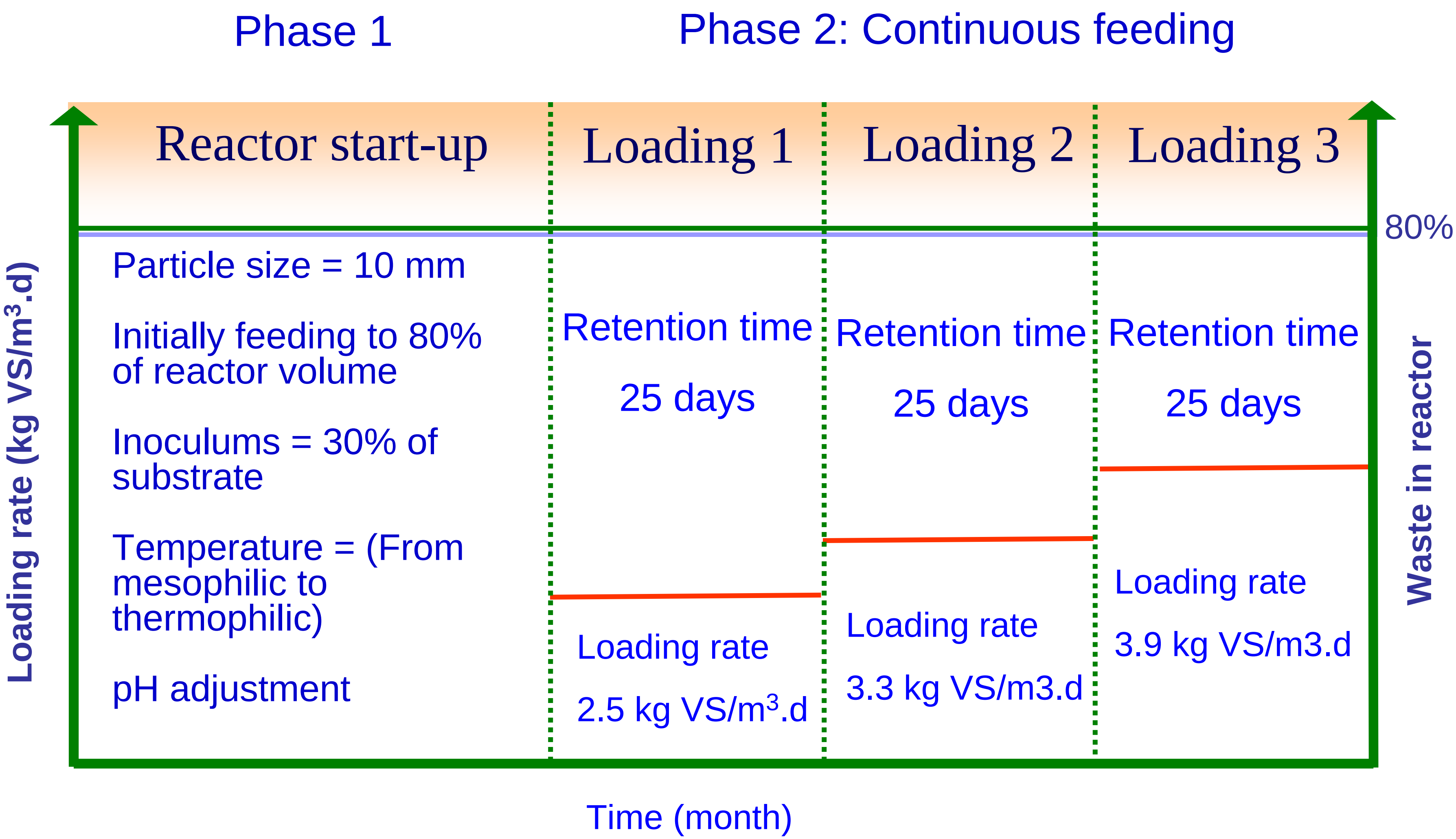
Wet gas meter

Anaerobic digestion system



Feeding hopper

Pilot Scale Experiment



Results and Discussions

1. Waste segregation in AIT
2. Experimental work
3. Conceptual framework

Waste Segregation in AIT

Treatment methods	Composition(%)
Recycling	4
Composting	3
Landfilling	93

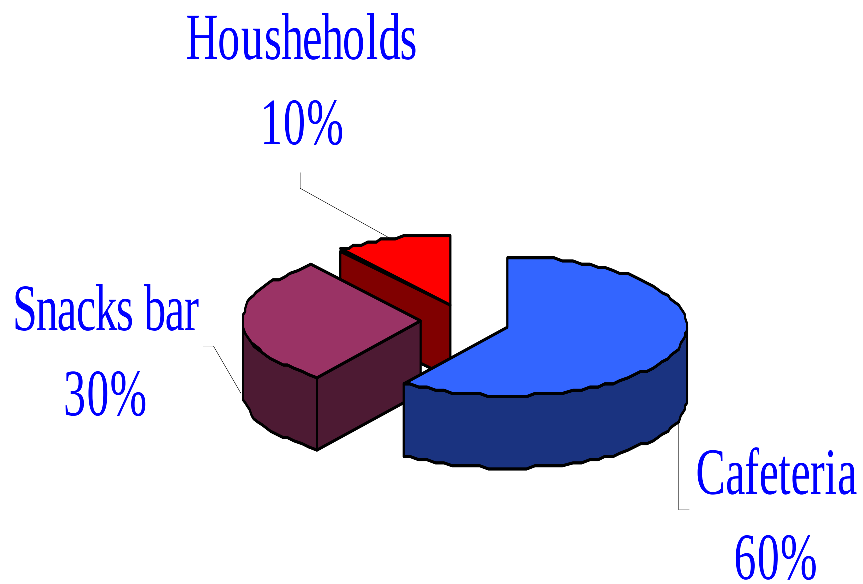
Total organic fraction = 60%

Total inorganic fraction = 40%

Source: Shamit, 2007

Total average amount of organic wastes collected = 67 kg/d

(Only 20 households were selected for initiation of waste segregation)



Posters for Waste Segregation

Waste Segregation Campaign

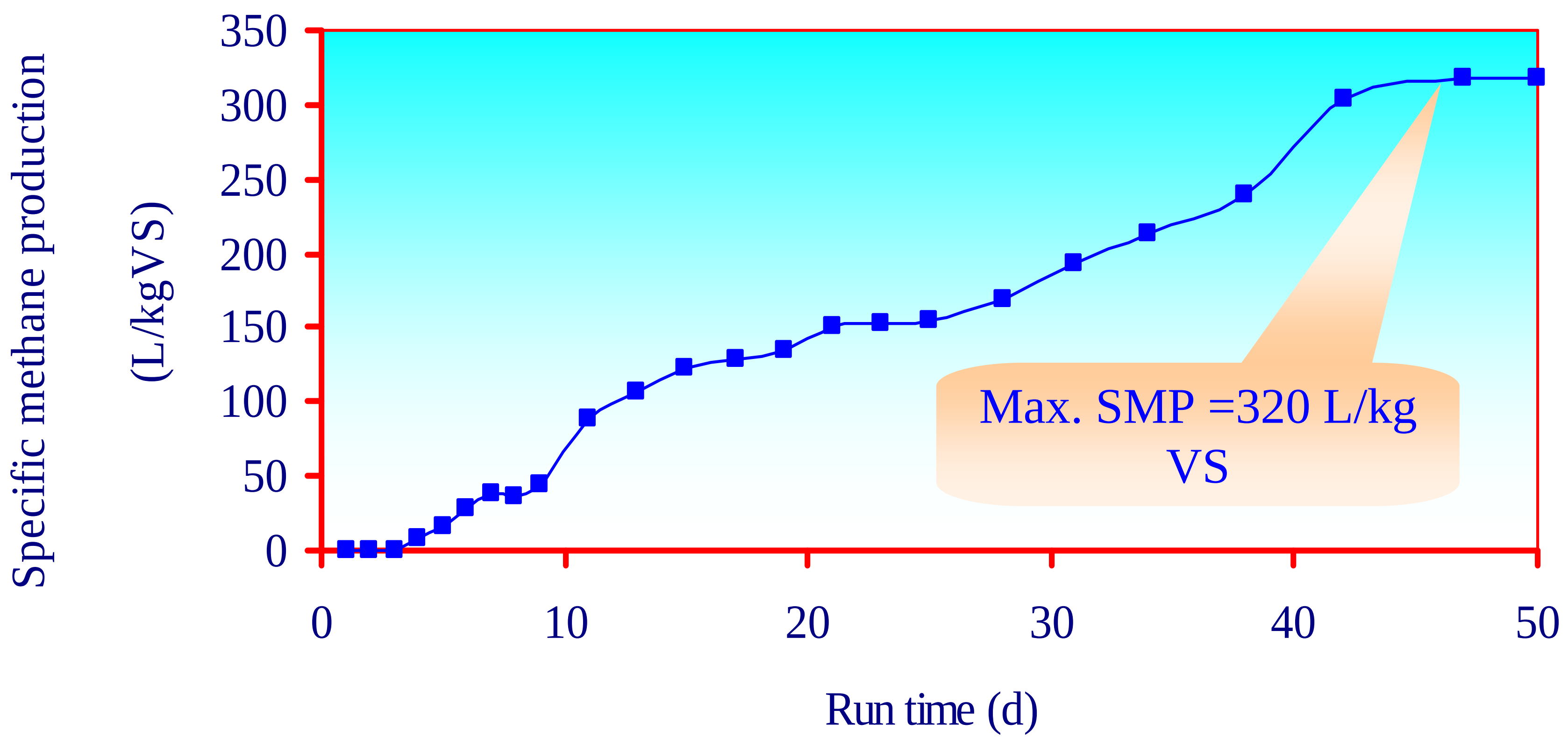
Garbage bins

Door to door campaign

Problems with Waste Segregation

- Complain about the timing of collection
- High amount of plastics were found while collecting the segregated wastes
- Some plastics, cans and other non-biodegradable materials were found in the sorted wastes
- How can we expect successful waste segregation from the municipality area where the level of education is not so high?

BMP Test



Page 58

Results and Discussions

Feedstock characteristics

High MC

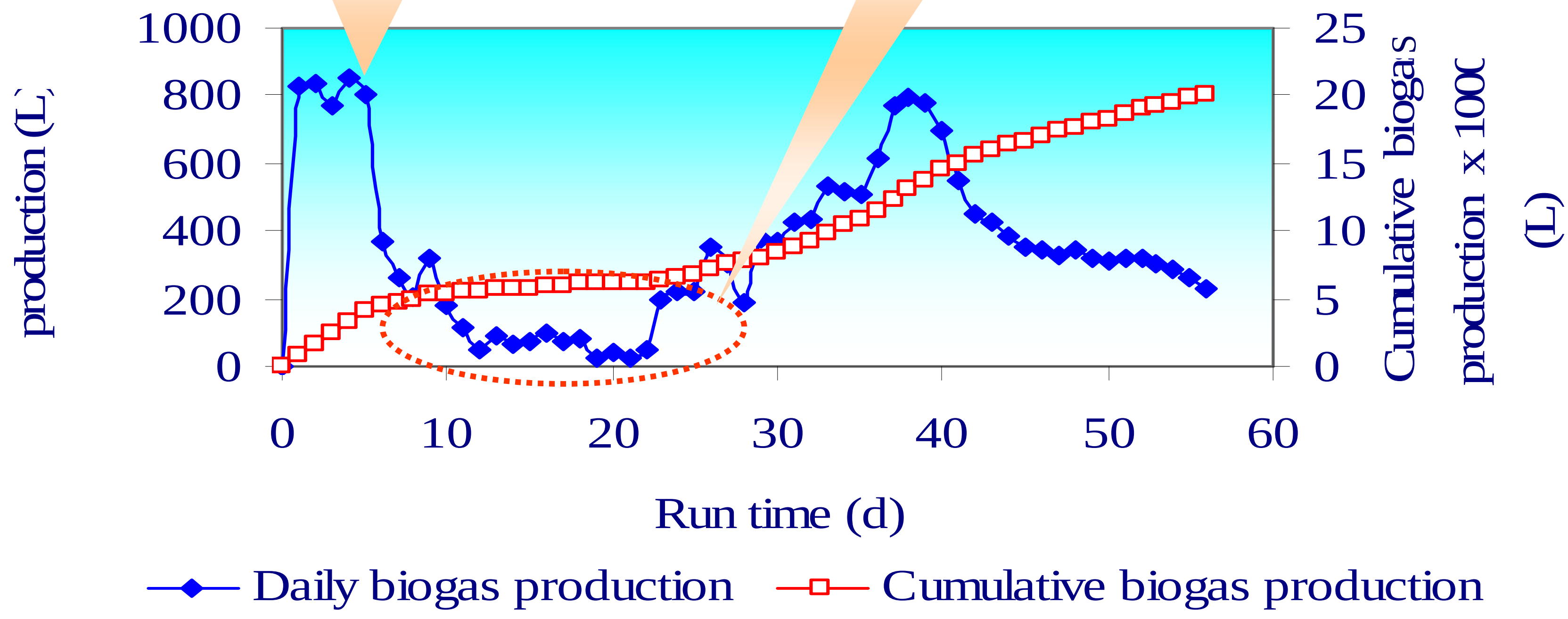
Parameters	Loading 1	Loading 2	Loading 3
Moisture content (%WW)	81.31	82.62	78.32
Total solids (%WW)	18.69	17.38	21.68
Volatile solids (%TS)	84.07	77.86	83.17
C/N ratio	20.52	21.01	21.96

Page 46

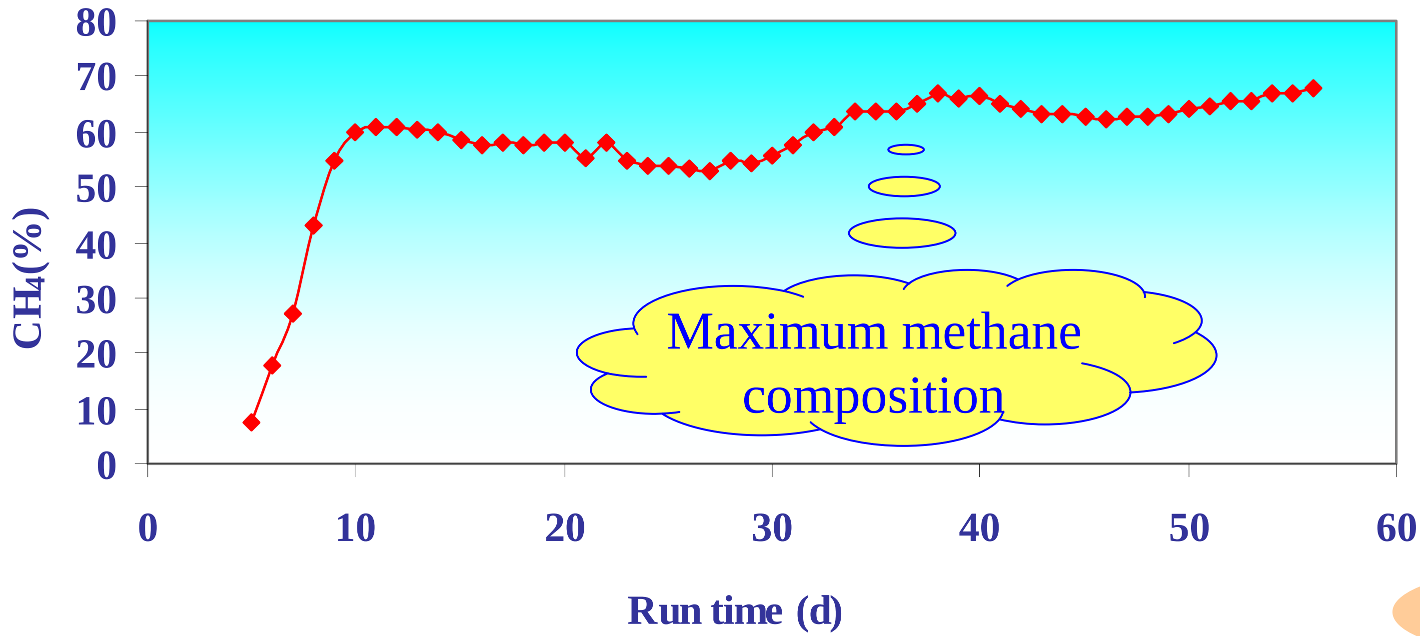
Phase 1: Biogas Production

High biogas generation due to entrapped air

No mixing



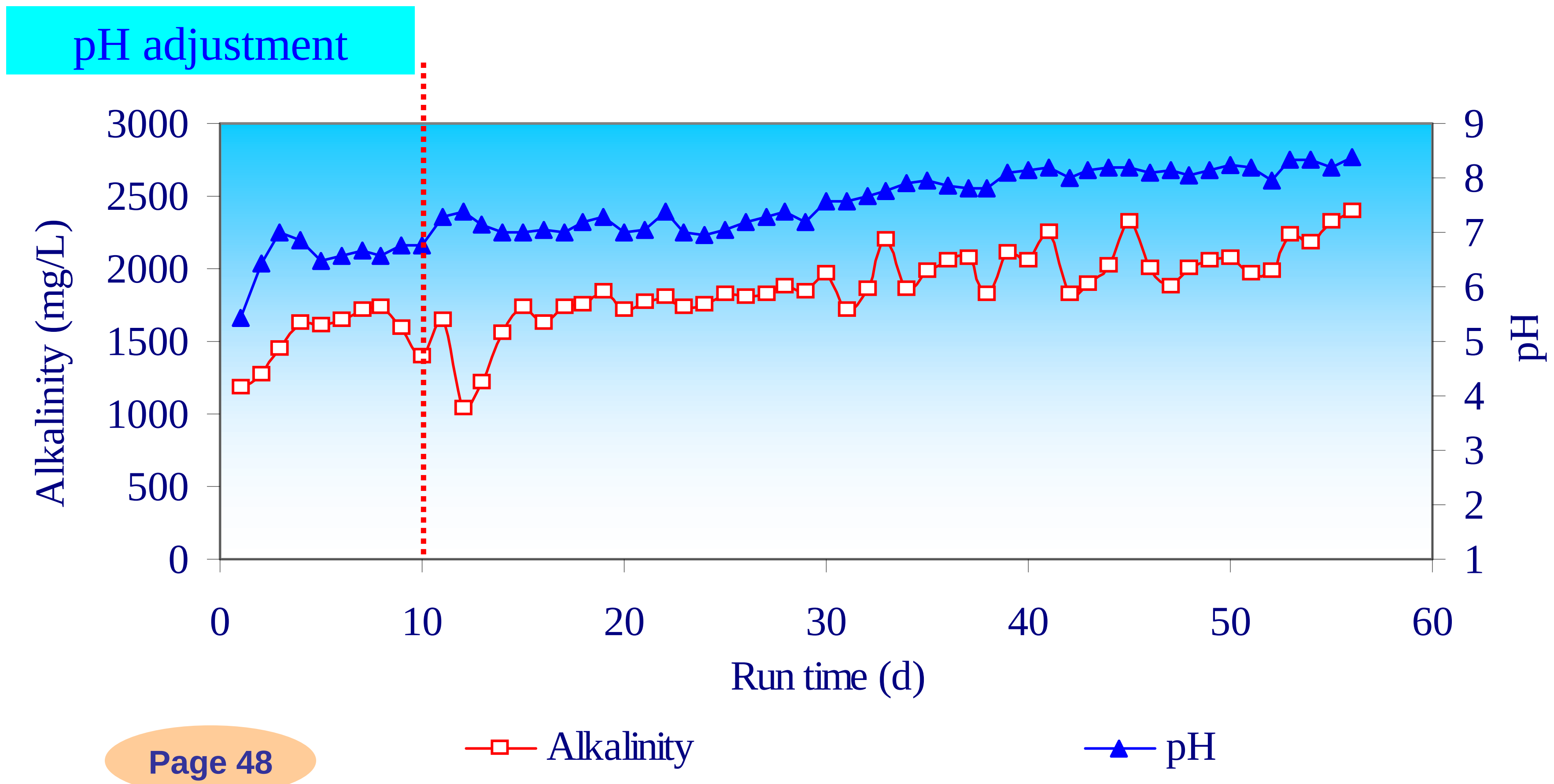
Phase 1: Biogas Composition



Page 48

Steady biogas composition was observed after 40 days and maximum daily biogas production was also achieved on same day.

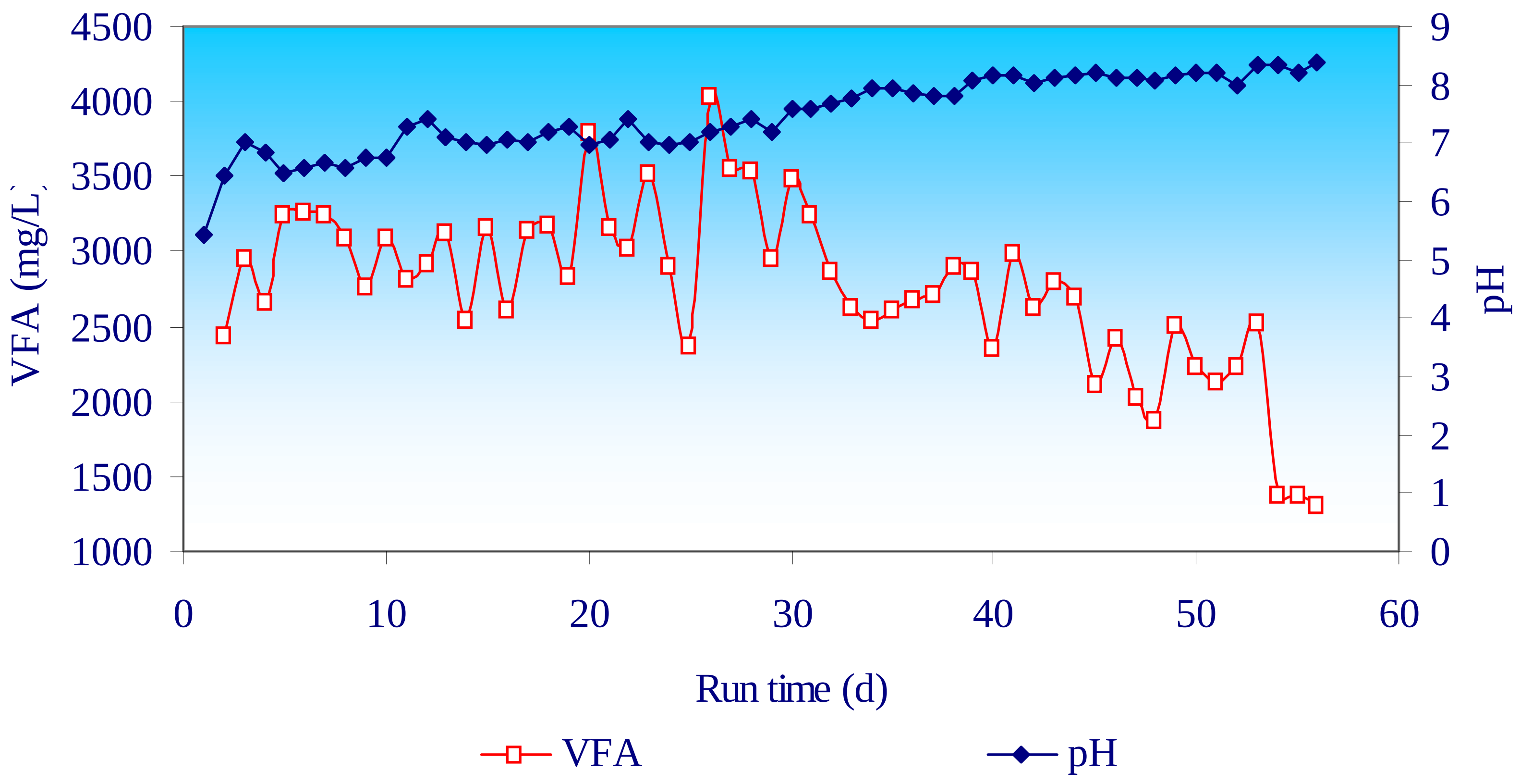
Phase 1: Leachate Characteristics



Page 48

Phase 1: Leachate Characteristics (Con't)

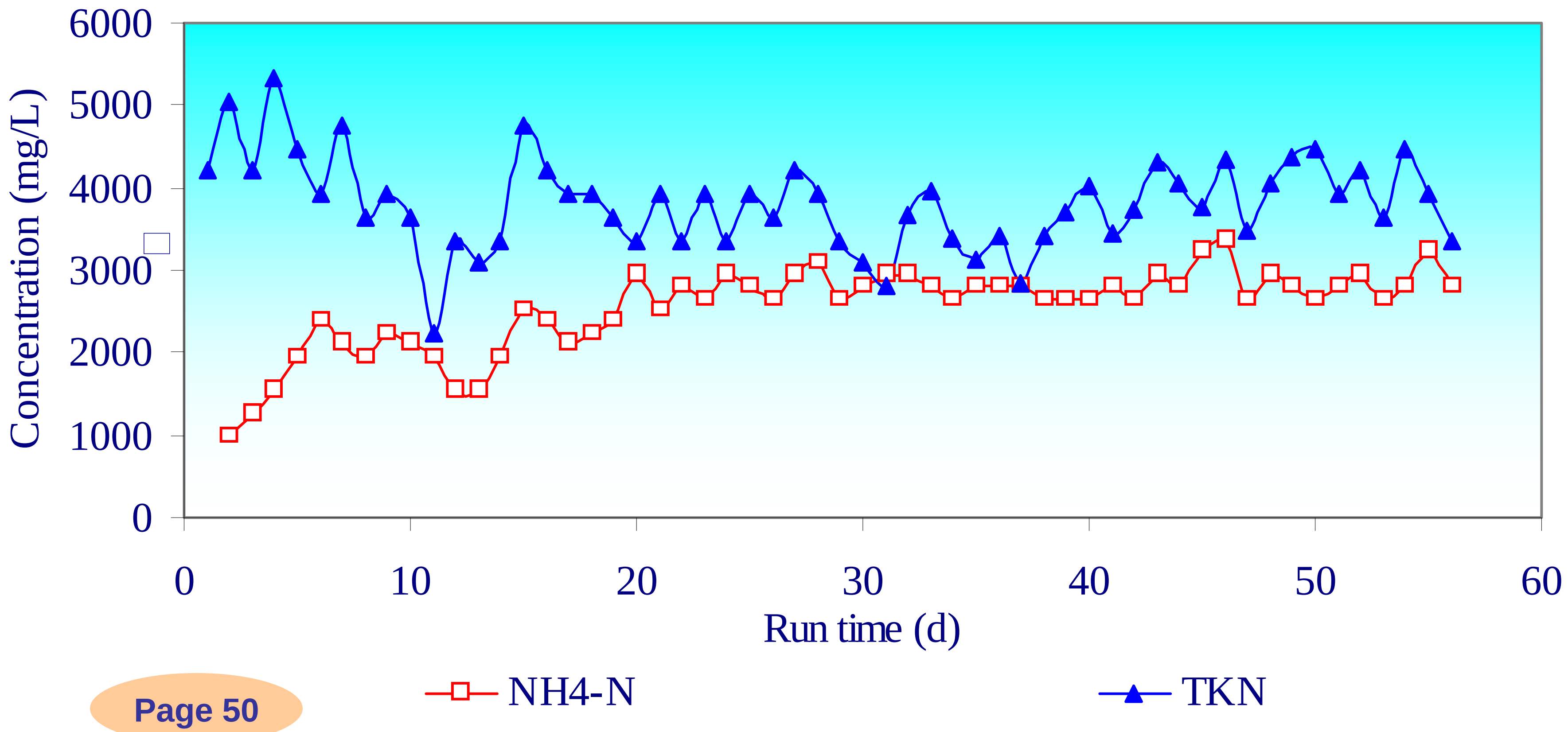
VFA concentration dropped after day 30



Page 49

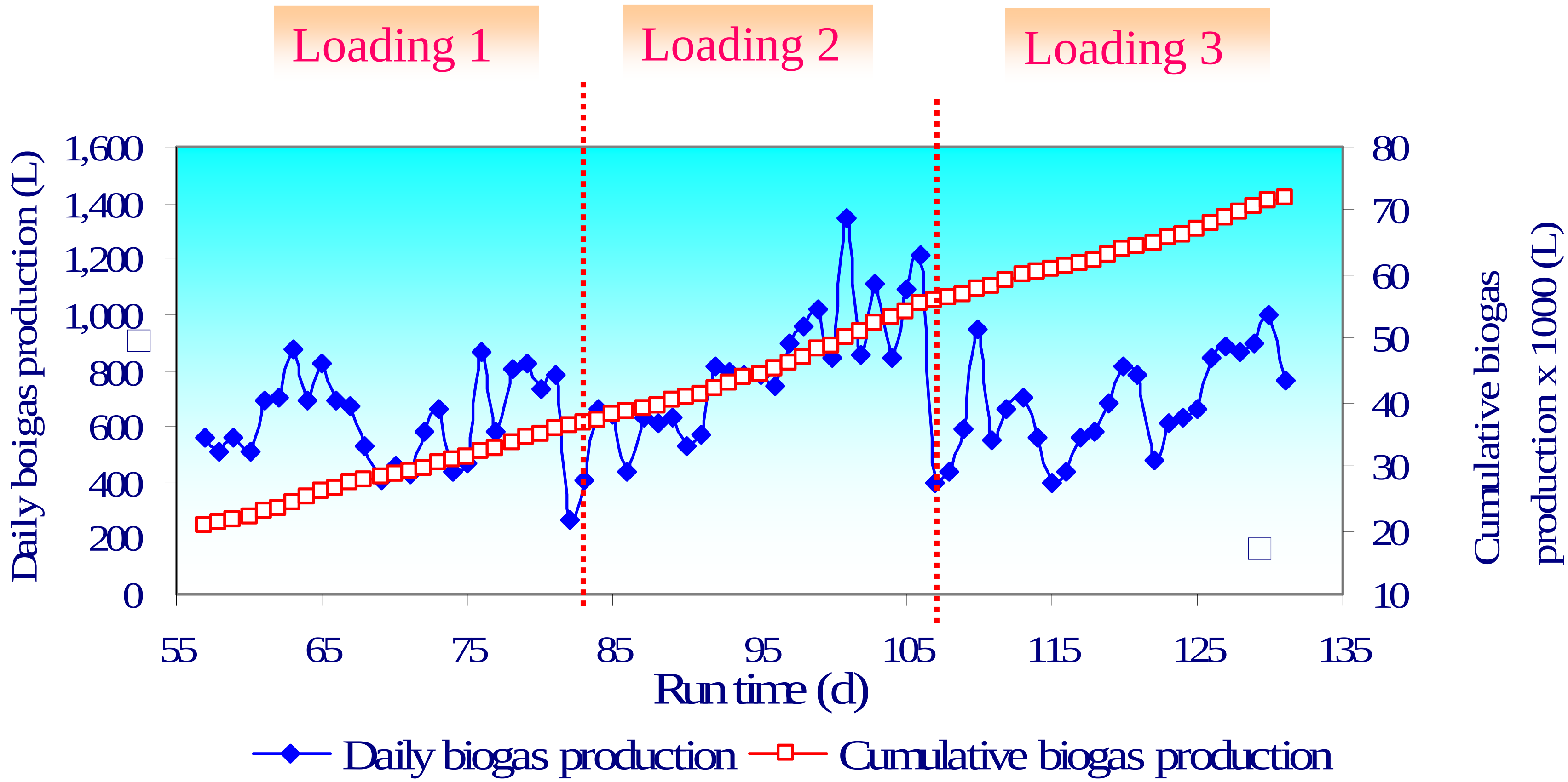
Phase 1: Leachate Characteristics (Con't)

Ammonia inhibition not occurred



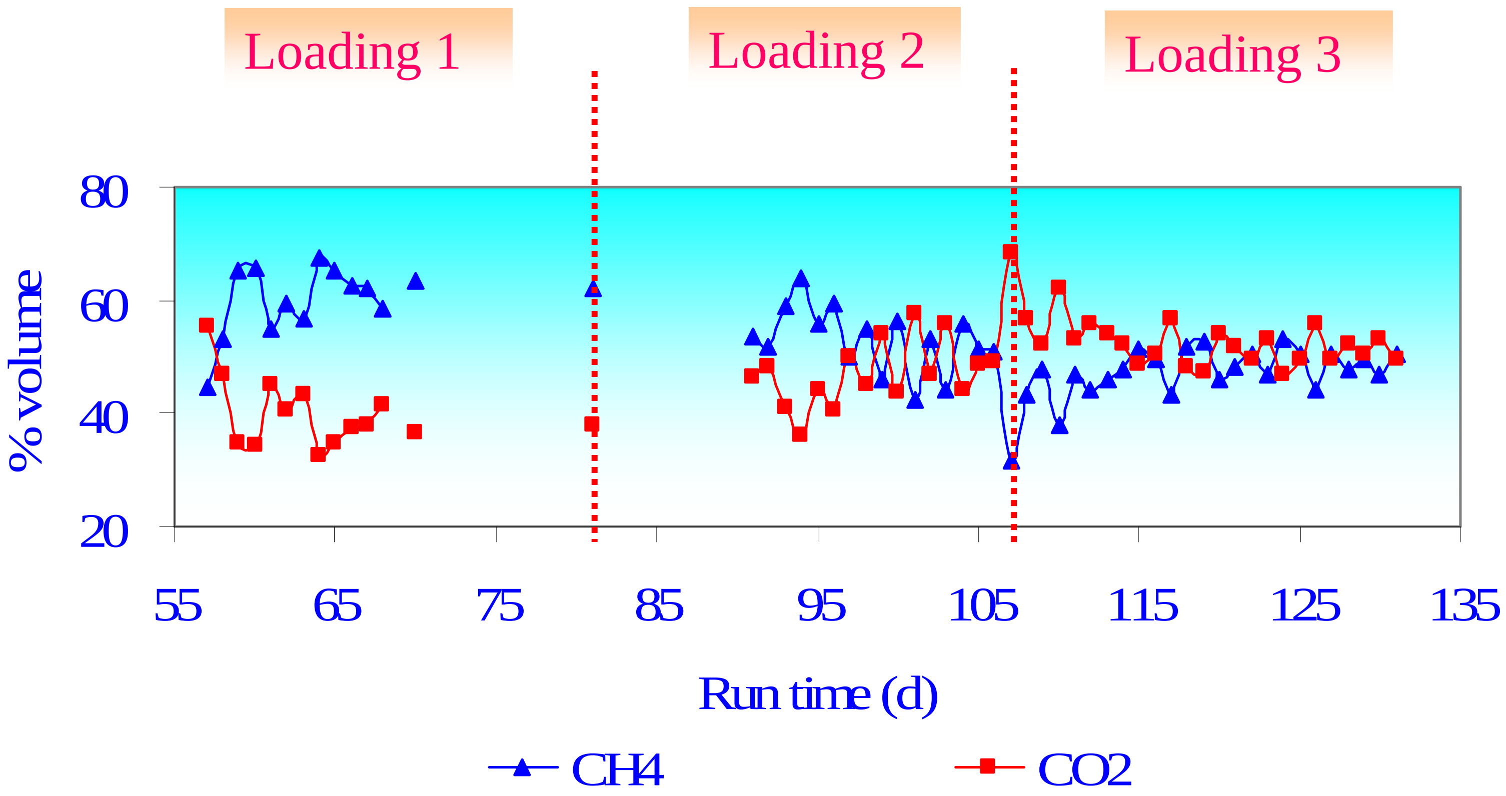
Page 50

Phase 2: Biogas Production



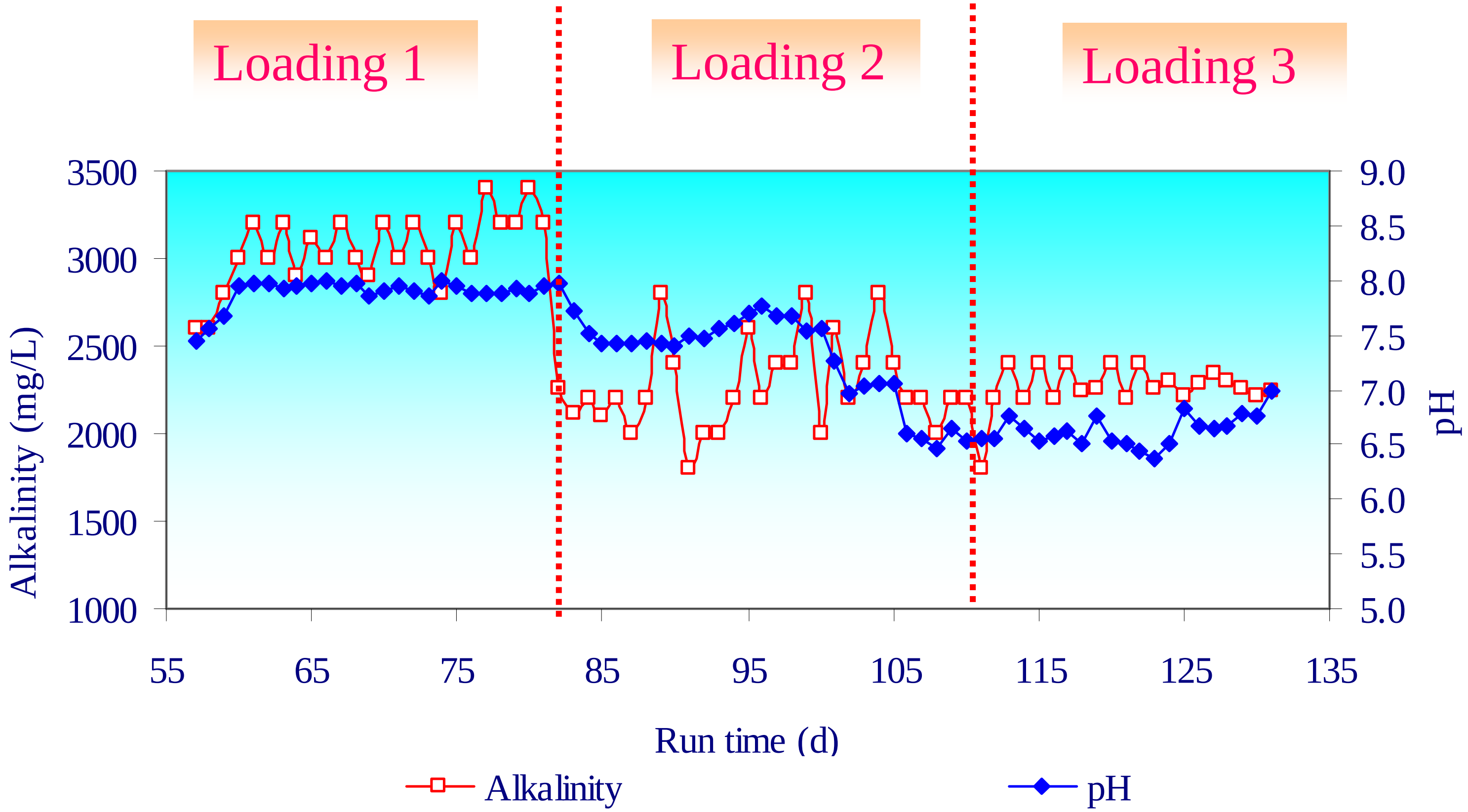
Page 51

Phase 2: Biogas Composition

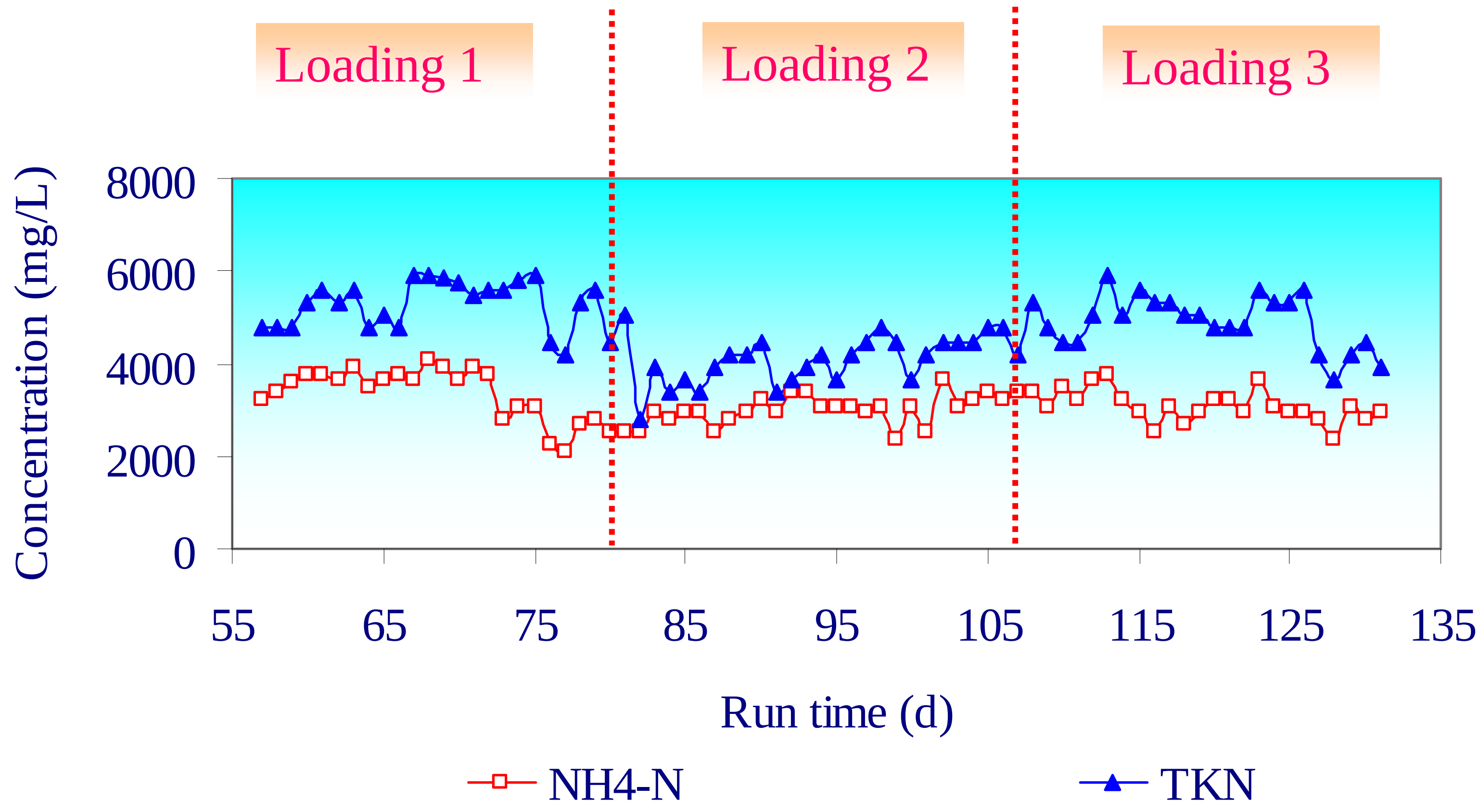


Page 51

Phase 2: Leachate Characteristics

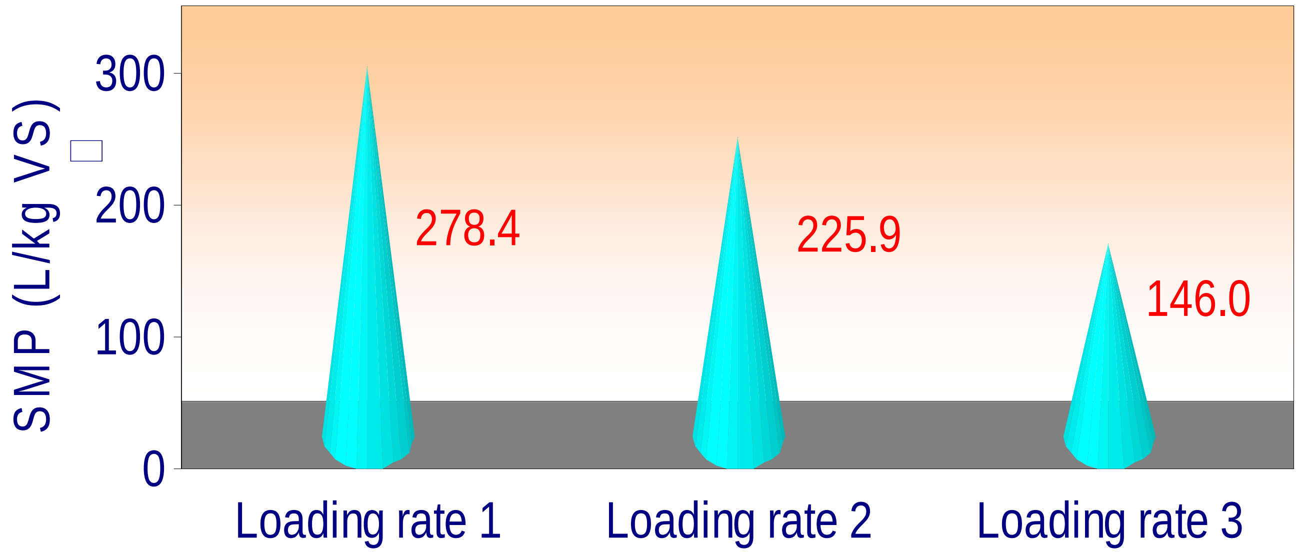


Phase 2: Leachate Characteristics (Con't)



Page 53

Overall Process Assessment

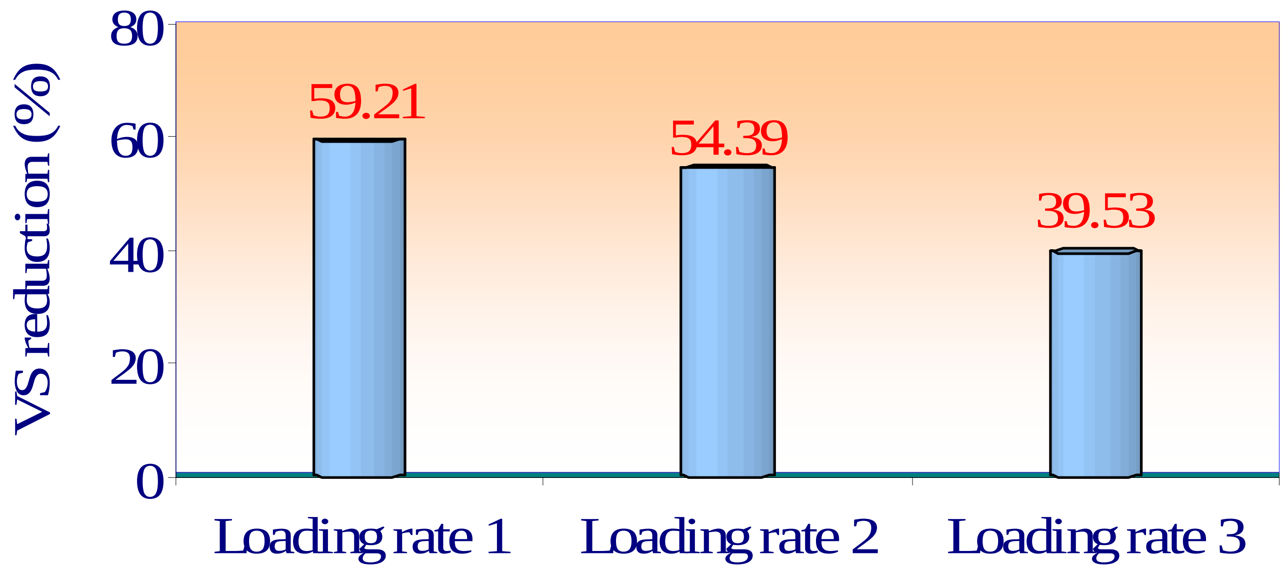


High SMP obtained with loading rate of 2.5 kg VS/m^3.d

Page 54

Overall Process Assessment (Con't)

High VS degradation at loading rate of 2.5 kg VS/m^3.d



Page 55

Digestate Quality

	Nutrients (%DM)			C (%)	C/N	Calorific value (MJ/kg)
	N	P	K			
Thai guideline	1	1	0.5	-	<20	15
Digestate	1.2	0.45	0.4	22.15	18.46	12.1

RDF potential

- Digestate can be used as biofertilizer
- Can be used as substrate for composting by blending with other materials

Page 57

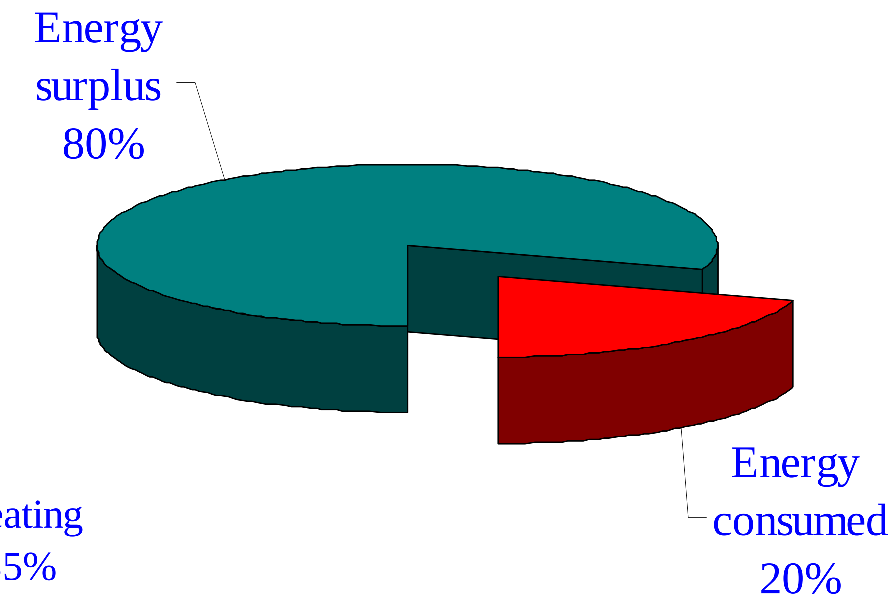
Mass Balance System

Descriptions	VS in Feedstock (kg/d)	VS loss in biogas (kg/d)	Conversion efficiency (%)	VS in Leachate (kg/d)	VS in digestate (kg/d)
Loading 1	1.410	0.810	60.12	0.068	0.500
Loading 2	1.830	0.995	57.14	0.159	0.640
Loading 3	2.160	0.855	41.45	0.011	1.170

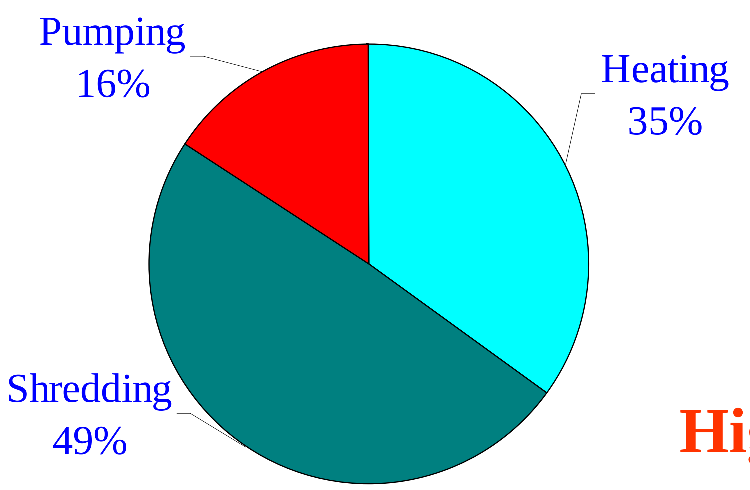
High performance with loading rate 1 (2.5 kg VS/m^3.d)

Energy Balance: Continuous

High revenue from system



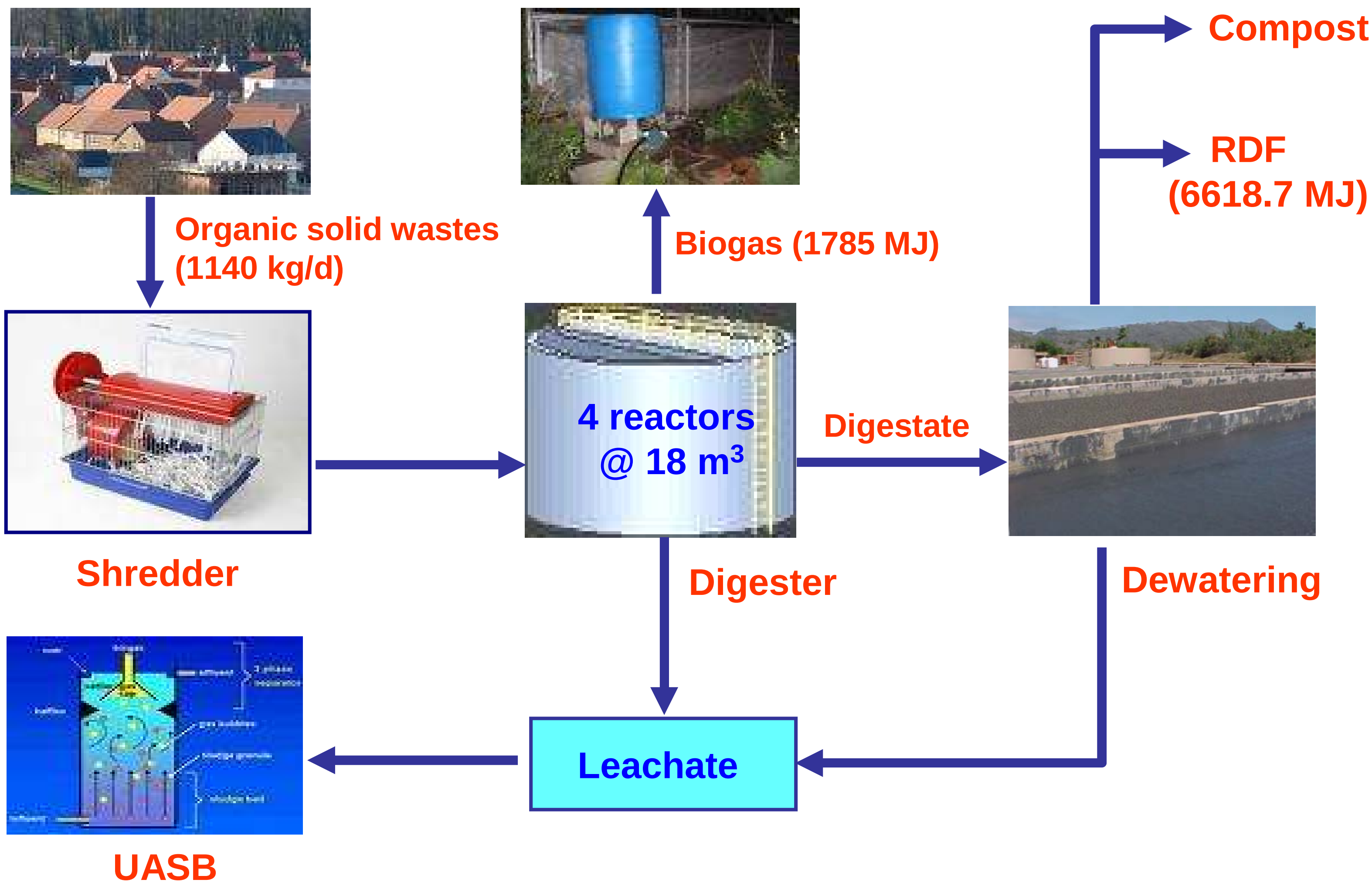
Page 61



High energy requirement for shredding

Page 60

Conceptual Framework for AD Plant



Conclusions

1. The specific methane production rate of 278.4, 225.9 and 146.0 L CH_4/kg VS were found in loading rate 1 (2.5 kg VS/m3.d), 2 (3.3 kg VS/m3.d) and 3 (3.9 kg VS/m3.d) respectively

2. Volatile solid reductions of 59.39 %, 54.39% and 39.53% were obtained during the loading rate 1, 2 and 3 respectively

3. By analyzing the nutrient contents of the residues, it was found that the digestate has a potential to be used as soil conditioner

4. Total energy surplus from this system obtained was 80% during continuous phase.

Recommendations

1. Source segregation of organic fraction of solid waste should be implemented in whole AIT community in order to have sustainable solid waste management

2. Since the methane is the excellent indicator of greenhouse effects, it should be trapped and should be either used or disposed properly

3. The percolate of the sludge drying bed should be further treated with Upflow Sludge Blanket Reactor (UASB) since the percolate and leachate obtained from digester still have high organic loadings.

4. The AD system should be operated into two stages in order to get higher methane yield and to control the process effectively

Thank you