ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN THERMOPHILIC CONTINUOUS OPERATION

by

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Abstract

The process for waste stabilization prior to landfill is very attractive in managing municipal solid waste (MSW). Thus, the main goal of this study is to assess the effectiveness of the anaerobic digestion method as the pretreatment technology of organic fraction of municipal solid waste (OFMSW) prior to landfill. On that account, a pilot study was conducted in inclined type horizontal anaerobic digester.

During the initial period of starting up the process, the reactor was operated under mesophilic condition (37°C), and then the system was shifted to thermophilic condition (55°C) by gradually increasing the temperature at the rate of 2°C per day. Result showed there was no any stress situation was found as methane composition in biogas keeps increasing and reached the maximum value of 66% at day 19. The highest volume of biogas production (520 L/ day) was also achieved at the same day.

In the second phase of this study, the influence of mass retention time (MRT) on the digestion process with higher organic loading rate was investigated. Two feeding rates of 2 kg VS/m^3.day and 2.5 kg VS/m^3.day were conducted under draw-feed mode are described with the retention time of 25 and 20 days, respectively. The highest VS degradation yield of around 51%, with a biogas production rate of 245 L/kg VS $_{add}$ were achieved with a retention time of 25 days. However, the methane content of the biogas generated from the reactor was in the range of 30–40%. The problem on the drop of methane concentration was traced on the technical problems on reactor configuration and not with the process. The fate of heavy metals in the digestion process was also investigated. This study confirmed that heavy metals and nutrients concentration of digestate complies with WHO guideline and can be used as fertilizer. The net energy yield from the process was also studied to indicate the energy surplus from the system. Moreover, the digestate from the process was analyzed for its calorific value content. Based on EURITS, the residue might have a potential to be used as a material for refuse derived fuel (RDF) since its calorific value was found to be 11.16 MJ/kg.

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List of Abbreviations

AD	Anaerobic Digestion
BMP	Biochemical Methane Potential
CAD	Continuos Anaerobic digestion
CH_3COOH	Acetic acid
CH_4	Methane
C_2H_5OH	Ethanol
C_2H_5COOH	Propionic acid
C_3H_7COOH	Butyric acid
$C_6H_{12}O_6$	Glucose
C/N	Carbon to Nitrogen ratio
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
DOC	Dissolve Organic Carbon
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectroscopy
IPPC	Intergovernmental Panel on Climate Change
H_2	Hydrogen
kWh	Kilo Watt Hour
MC	Moisture Content
MSW	Municipal Solid Waste
N_2	Nitrogen
ND	Non Detectable
NH_3	Ammonia
NH_4-N	Ammonia Nitrogen
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate
RT	Retention Time
RVS	Refractory Volatile Solid
SWM	Solid Waste Management
SEBAC	Sequential Batch Anaerobic Composting
STP	Standard Temperature and Pressure
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solid

Chapter 1

Introduction

1.1 Background

Sustainable environmental management is recently becoming an issue of global concern. Around the world, solid waste management becomes an important issue in urban areas. Currently, the generation of wastes has gained an important consideration in modern societies as a result of changes in habits and lifestyle of consumers, along with economic development. Due to the steady increase in population, urbanization, and industrialization, Municipal Solid Waste generation has been increasing over the last decade. For example, in Thailand, about 38,000 ton/day of refuse was collected in the year 2002 as compared to 29,000 ton/day in 1992 (Chaya & Gheewala, 2006). An important feature often cited when dealing with urbanization of the developing world is the rapid growth of cities and metropolitan areas. Since Asia urbanizes, solid waste production increased as urban residents generate 2-3 times more solid waste than the rural counterparts. Urban areas in Asia today generate about 760,000 tons of waste per day, and by 2025 will produce about 1.8 million tons per day (Chaya & Gheewala, 2006). Moreover, emerging mega cities will increase solid waste production. By 2015, an estimation of 21 cities in the world will have populations of 10 million or more, ten of these cities will be in Asia (Wheler, 2004). The above mentioned development will lead to the use of desperate measures in urban solid wastes management unless a critical management and disposal is considered.

The increasing waste generation and rising proportions of packaging and toxic compounds commingled in MSW will lead to problems in the disposal of wastes. Uncontrolled landfilling of waste leads to pollutant emissions over long periods of time which requires appropriate emission control and treatment methods. Furthermore, in cities of developing countries, the main disposal practice for MSW is open dumping. Thus, these dumpsites are in uncontrolled manner, creating considerable health, safety, and environmental problems, especially when high percentage of organics combined with much plastic that forms layers when compacted, contributes to the build up of methane gas at dumps in cities like Bangkok and Manila, so accidents like fire and explosions have occurred (UNEP, 2005). It seems to be an oncoming disaster that the amount of MSW generation is in the increasing phase as a result of urbanization and industrialization. These circumstances can be found all over the world and creating new strategies are being developed for waste management as the public awareness on the environmental hazards from landfills are increasing (Mtz-Viturtia et al., 1995). The above factor is important when considering the waste management issues. The promotion of waste reduction at source or waste minimization and recycling are important components of modern waste management strategies. Moreover, waste minimization at source is more preferred (Letras, 2001). Nevertheless, even when the minimization and recycling potentials are fully applied, the remaining organic residual fraction need to be disposed of. Thus, the burdens resulting from landfilling can be minimized by pre-treating the waste prior to final disposal and therefore limiting its environmental emission potential (Fricke et al., 2005)

Various alternatives are available for pretreatment of organic fraction of municipal solid wastes before disposal namely, biological, physical and chemical processes (Environmental Agency, 2006). However, the selection of any treatment method always has its own positive and negative aspects and it depends on waste compositions, financial and institutional framework or country policies, and waste quantities (Fricke et al., 2005). Biological processes; which comprise of aerobic composting and Anaerobic Digestion (AD), provide advantages due to its natural treatment processes over other technologies. Treating organic wastes by AD is an attractive method for stabilization of organic wastes into methane (CH_4) and compost. It is the method which is used by nature under anoxic conditions. Therefore, it is placed in the context of end product, energy use, recycling and environmental aspects in term of greenhouse reduction in general (Braber, 1995). AD also showed an excellent Life Cycle Analysis (LCA) performance as compared to other treatment technology like composting or incineration as it can improve the energy balance (Mata-Avarez, 2003). Biogas is a desirable energy product which can be used directly as the source of energy. In addition, the residues are stable and serve as excellent compost for the agricultural purpose as well as reduce pathogenic bacteria and then decrease the possibilities of disease transmission (Torres-Castillo et al., 1995).

1.2 Problem Statement

Several available options for AD are now being taken into consideration. The great diversity of reactor designs is matched by a large variability of waste composition and choice of operational parameters such as retention time (RT), solids content, mixing, recirculation, inoculation, number of stages, temperature, etc. However, the general overview of anaerobic digestion can be then classified by the level of solid content, number of stages, and mode of operations.

In connection with levels of solid content, there are two types of operation namely, wet (low solid) and dry (high solid) processes. In the wet process, the total solids of substrate are only 10-15%. So the feedstock comprises mainly of slurries and required a bigger reactor volumes and expensive post treatment (RISE-AT, 1998). In dry mode or high solid processes, the feedstock contains a dry solid of 20-40%. The process takes place in solid beds, without addition of water to make slurries and no mixing is provided.

Depending on the number of stages, one, two or multiple stages have been categorized. In one-stage systems, all these reactions take place simultaneously in a single reactor, while in two or multi-stage systems, the reactions take place sequentially in at least two reactors (RISE-AT, 1998). Industrialists, on the other hand, prefer one-stage systems because simpler designs suffer less frequent technical failures and have smaller investment costs. Biological performance of one-stage systems, for most organic wastes is, as high as that of two-stage systems, provided the reactor is well designed and in good operating condition. However, two-stage or multi-stage systems have been utilized, in which the conversion of Organic Fraction of Municipal Solid Waste (OFMSW) to biogas is mediated by a sequence of biochemical reactions which do not necessarily share the same optimal environmental conditions. Optimizing these reactions separately in different stages or reactors may lead to a larger overall reaction rate and biogas yield. Likewise, it is not an attractive design as far as practical operation and maintenance costs are concerned.

Batch and continuous reactors are categorized based on the mode of operation. In Sequential Batch Anaerobic Composting (SEBAC) reactors, the reactor vessel is loaded with raw feedstock and inoculated with digestate from another reactor. It is then sealed and left until thorough degradation has occurred. The digester is then emptied and a new batch of organic mixture is added. Nevertheless, in a continuous process, the reactor vessel is fed continuously with digestate material; fully degraded material is continuously removed from the bottom of the reactor (RISE-AT, 1998). However, there are some disadvantages of the batch process. Adhikari (2006) has reported that, in a batch process, a steady state is never achieved. Moreover, the land required for the plant is large and it is not practical due to the continuously increasing generation of wastes. Additional loading and unloading is another common issue. These features lead many researchers to consider the aspects of continuous reactor design.

Another mode of operation namely combined process has been utilized by Lien (2004) in a pilot scale reactor. In this process three stages of pretreatment were carried out. In the first stage, flushing with tap water along with the application of micro-aeration was applied to enhance hydrolysis/acidification and some part of the intermediate product was removed from the reactor. Finally, air flushing completed the process of pretreatment before its final disposal into the landfill.

Juanga (2005) reported that the biogas production in thermoplilic systems is greater than that in mesoplilic systems. Moreover, smaller particles are also effective in producing a higher yield of biogas. Furthermore, Adhikari (2006) has reported that the major problem in a vertical continuous reactor under high solid AD is the withdrawal of the digestate. It is therefore necessary to study the digestion operation in inclined type horizontal digester under the continuous mode of operation.

1.3 Objectives of the Study

The goal of this study is to assess the effectiveness of the AD method as the pretreatment technology of OFMSW prior to landfill. This pretreatment will result in reduction as far as possible negative effects on the environment, in particular in the reduction of mass, volume and stabilization of municipal solid waste before landfill. Additionally, it plays an important role in global environment including greenhouse gas emission reduction. The specific objectives of this research are the following:

To develop operational design criteria for the horizontal anaerobic reactor under continuous operation using OFMSW as substrate;

To evaluate the performance/efficiency of a continuous reactor in continuous mode of operation;

To investigate the fate of heavy metals during the digestion period using material balance analysis.

1.4 Scope of the Study

OFMSW was used as a substrate, which was collected from the Taklong Municipality dumpsite, Pathumthani, Thailand.

The AD of OFMSW experiments was conducted in the continuous mode of operation using a semi-inclined type anaerobic digestion (pilot scale reactors).

An important operational condition such as maximum temperature of thermophilic (55°C) and a reduced particle size of 10 mm were used in this study.

Biochemical Methane Potential (BMP) test was conducted in laboratory scale.

Chapter 2

Literature review

2.1 Introduction

Due to rapid economic and population growth, along with urbanization, it is common to see many developing countries are struggling to provide a proper waste management system; a basic municipal service taken for granted by the developed world (Vidanaarachchi, et al., 2006). As urbanization continues to take place, the management of solid waste is becoming a major public health and environmental concern in urban areas of many developing countries. The concern is serious, particularly in the capital cities (Ogawa, 1996). A study by Zurbrugg (1999) suggested that problems and issues of MSW management are of immediate importance in many urban areas of the developing world. The main factors affecting the waste generation are population and mean living standard of the country (Daskalopoulos et al., 1998). The existence of a wide variety of processes and technologies for MSW treatment, or even the various possibilities of combining them, have given rise to the appearance of a number different structures and solutions for MSW treatment (Magrinho et al., 2006). Sanitary landfilling is one of the most challenging approaches in waste management practices. It is known as the final option method in the hierarchy of waste management, and is the method that has been adopted for MSW treatment. However, even with sanitary landfilling being the most common method of MSW management, there is no landfill gas energy recovery (Miranda &Brack, 1997). Nevertheless, there also some common problems arising from waste disposal at landfills due to the limited land resources available and the population is kept increasing (Jin et al., 2005). This would make landfills as the ultimate disposal of waste seems unattractive. Additionally, the national and international agencies are aware of the detrimental impact from an environmental point of view.

In the present situation, according to the most recent technologies, the optional solution for MSW treatment is not fully established especially in developing countries. However, waste minimization, production, prevention, reuse, recycling, recovery, and incineration, are attractive methods since there are limitations in landfilling in some European countries. Nevertheless, again, the organic fraction of waste still remains in landfills, which will definitely cause problems to the environment such as; air pollution, surface and ground water pollution. This may lead to global environmental concern. Global warming and climate change from the huge amount of gases is emitted.

Treating the OFMSW has become the most attractive approach. There are many technologies available and each one of them has its own advantages and disadvantages. AD is one of the challenging options since volume and mass reduction as well as less energy consumption and CH_4 yield can be obtained from the process. It is the process by which its operation is done in the absence of oxygen and requires less energy input. Moreover, the digested waste can also be utilized as the fertilizer for agricultural purposes if further treatment has been made.

This chapter will describe the current trends of solid waste generation and its characteristics in developing countries. Additionally, the concept of pretreatment prior to landfill of OFMSW by biological methods as well as some related information on AD will be summarized. Furthermore, the details of AD process, the constraints and solutions in order to optimize the biogas production are described. Additionally, various kinds of anaerobic operation are explained in this section. Overall, this chapter focuses on the important roles of anaerobic digestion in MSW management in a sustainable manner.

2.2 Solid waste generation and its characteristics in developing countries

Solid waste can be defined as material, which is not in liquid form, and has no value to the person who is responsible for it. The term MSW, refers to solid wastes from houses, streets and public places, shops, offices, and hospitals, which are very often the responsibility of municipal or other governmental authorities (Zurbrugg, 1999). Waste is created by human activities. However, the amount of waste generated is still depends on the socio-economic factors and the standards of living of the people. As the economic growth and the number of mega cities are rising rapidly mainly in Asia, has lead the developing countries encounter with solid waste management problems than that of the industrial countries (Zerbock, 2003). Globally, (MSW) generation on a daily basis vary significantly. Economic standing is one primary determinant of how much solid waste a city produces (World Resources Institute, 1996 cited in Zurbrugg, 2002). Table 2.1 shows waste generation rates for some selected Asian low and middle income countries.

Table 2.1 Waste generations rates of some Asian Countries

Country	**Waste generation [kg/capita day]**
Nepal	0.2 - 0.5
Cambodia	1.0
Lao PDR	0.7
Bangladesh	0.5
Vietnam	0.55
Pakistan	0.6 - 0.8
India	0.3 - 0.6
Indonesia	0.8 - 1.0
China	0.8
Sri Lanka	0.2 - 0.9
Philippines	0.3 - 0.7
Thailand	1.1

Source: Zurbrügg, 2002

Importantly, in the consideration of the waste management plans and treatment technology, waste composition has a significant impact on selecting the most appropriate technology. Indeed, waste composition in developing countries significantly varies with the developed nations. Although solid waste generation rates in low-income countries average from only 0.4 to 0.6 kg/person/day, as compared to 0.7 to 1.8 kg/person/day in fully industrialized countries. Many researchers (Cointreau, 1982; Blight & Mbande, 1996; Arlosoroff, 1982 cited in Zerbock, 2003) have found several common differences in the composition of solid wastes generation in developing nations as the following:

Waste density 2-3 times greater than industrialized nations,

Moisture content (MC) 2-3 times greater,
Large amount of organic waste (vegetable matter, etc.),
Large quantities of dust, dirt (street sweepings, etc),
Smaller particle size on average than in industrialized nations.

These differences from industrialized nations must be recognized both in terms of the additional problems they present as well as the potential opportunities which arise from their waste composition. Figure 2.1 represents the typical waste generation in some selected Asia countries.

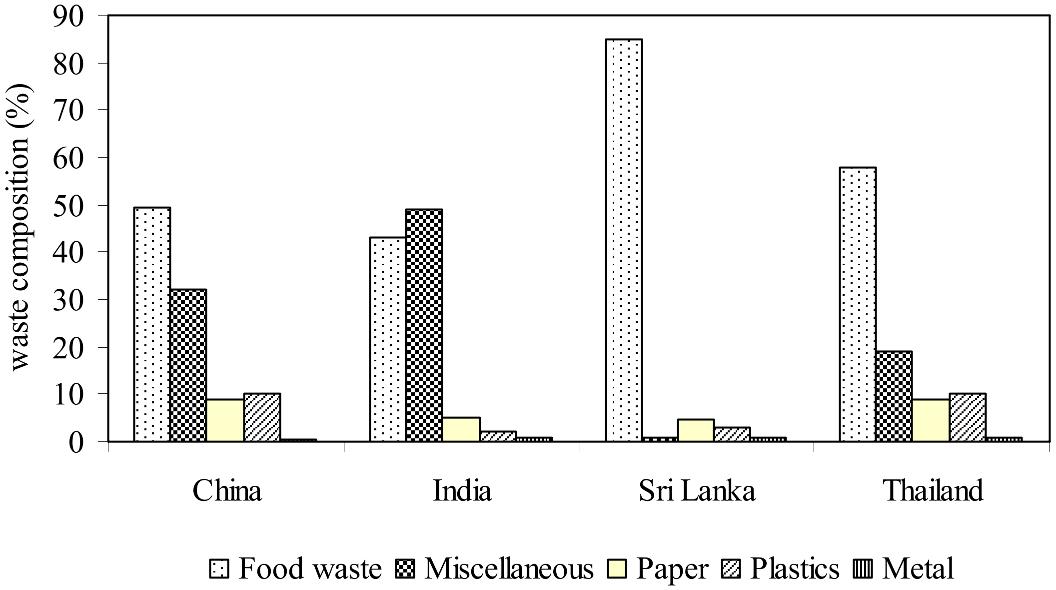

Figure 2.1 MSW composition in selected Asian countries
(Visvanathan et al., 2004)

The high content of biodegradable matter and inert material, results in high waste density (weight to volume ratio) and high moisture content. These physical characteristics significantly influence the feasibility of certain treatment options. Systems operating well with low-density wastes such as in industrialized countries will not be suitable or reliable under such conditions. In addition, to the extra weight, abrasiveness of the inert material such as sand and stones, and the corrosiveness caused by the high water content, may cause rapid deterioration of equipment. Wastes with a high water or inert content will have low calorific value and thus, also not be suitable for incineration.

2.3 Potential waste generation trend

The production and composition of MSW vary from one country to another and are influenced by various factors including region, climate, and extent of recycling, selection of disposal method, collection frequency, season and cultural practices. Interestingly, Visvanathan et al. (2004) reported that the generation trend situation of selected Asian country like Thailand showed the steady increase of solid waste production with time. Specifically, the annual increase of MSW generation in Thailand is depicted on Figure 2.2.

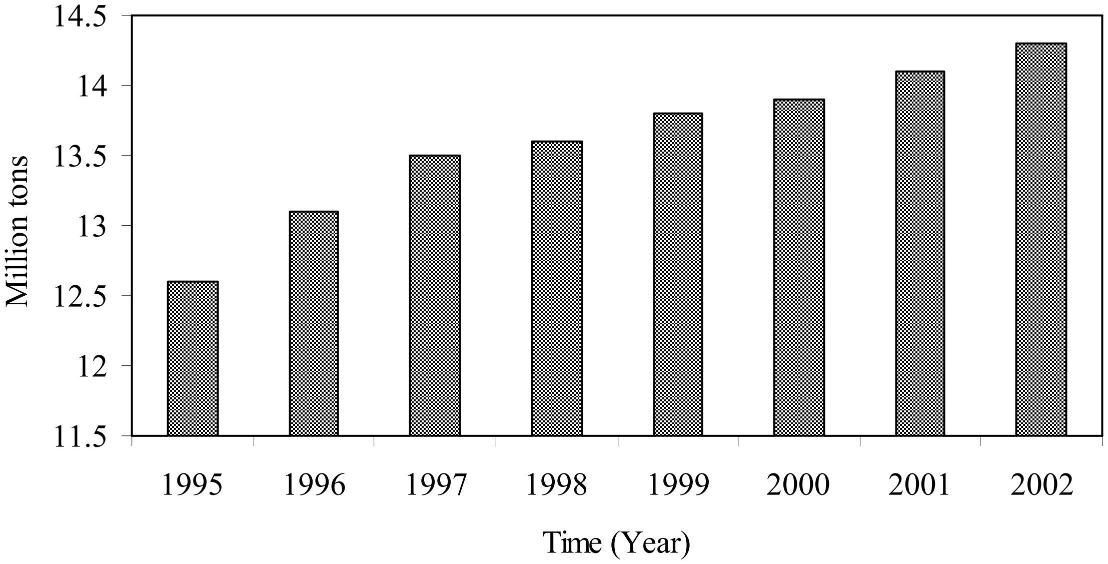

Figure 2.2 Annual MSW generation in Thailand

2.4 Current solid waste management strategies

Here, some examples of solid waste management systems encountered in low-income Asian countries are elaborated. The description does not mean to be completed, but intends to show some typical difficulties which most of municipalities are facing and elucidate what innovative solutions and approaches have been implemented.

A typical waste management system in low-income Asian countries can be described by the elements:

Household waste generation and storage
Reuse and recycling on household level (includes animal feed and composting)
Primary waste collection and transport to transfer stations or community bins
Management of the transfer stations or community bins
Secondary collection and transport to the waste disposal site
Waste disposal in landfills

Recovering and recycling usually takes place in all elements of the systems and is widely practiced by the informal sector "waste pickers" or by the solid waste management staff themselves for extra income. Recovered and recyclable products then enter a chain of dealers, or processing before they are finally sold to manufacturing enterprises. However, the waste management application does not match with the potential composition as the amount of organic fraction disposed to landfill will create some environmental problems.

2.5 Problem associated with SWM

Open dumps, unfortunately still mostly observed in developing countries, where the waste is dumped in an uncontrolled manner, can be detrimental to the urban environment. Many governments now acknowledge the dangers to the environment and to public health derived from uncontrolled waste dumping. However, officials often think that uncontrolled waste disposal is the best that is possible. Financial and institutional constraints are one of the main reasons for inadequate disposal of waste, especially where local governments are weak or underfinanced and rapid population growth steadily continues (Kum et al., 2005). Many governments even have great difficulties in trying to define their actual SWM costs, as very often no detailed cost accounting is in place. When SWM systems based on user fees are in place (government franchise to private company), often the fees barely cover costs of collection and transportation only. Practically, there is no financial resource for safe disposal of waste. Financing this part of the solid waste management cycle is made even more difficult as most people are willing to pay for the removal of the refuse from their immediate environment but then "out of sight, out of mind" is generally not concerned with its ultimate disposal.

Focusing of MSW management in many developing countries is on waste collection, with a lack of consideration for waste treatment or disposal. While collection would help to remove waste from the generators, collected waste is often disposed of in open dumps without concern for environmental degradation and human health impacts (Vidanaarachchi et al., 2006). Open dumping is the most economical method which is dominantly practicing except for developed countries (Visvanathan, et al. 2004). Figure 2.3 shows the disposal methods practiced in selected Asia countries while Table 2.2 illustrates the disposal method in some countries in Asia and the Pacific region. Most organic materials are biodegradable and can be broken down into simpler compounds by aerobic and anaerobic microorganisms, leading to the formation of gas and leachate in landfills. Therefore, the appropriate measures are needed to control the environmental impacts, or to eliminate or minimize these impacts (Fadel et al., 1997). Rather than dispose such residues, after dewatering, these could be composted aerobically, but with AD without any pre-treatment, with energy recovery, seems to be a more attractive method for the treatment of the above mentioned biodegradable waste (Shama et al., 2000).

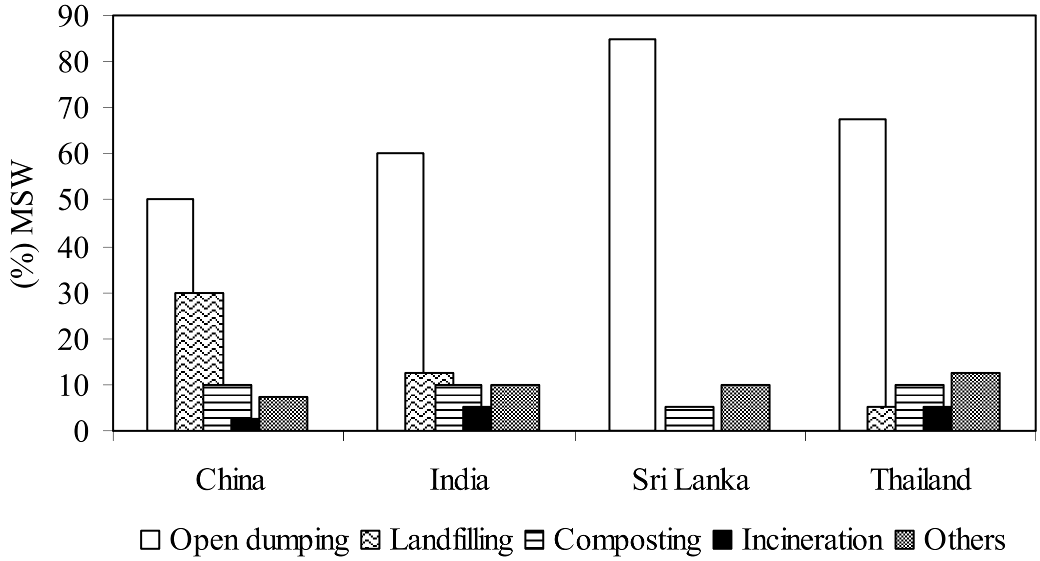

Figure 2.3 MSW disposal practiced in selected countries

2.6 Pretreatment technology prior to land filling

Pretreatment fulfills the first three components of the waste hierarchy manely: reduction, reuse, recovery and disposal. As stated by SITA UK (2002), the following three criteria are considered to be fulfilled by pretreatments technologies.

It must be a physical/ thermal/ chemical or biological process including sorting;
It must be permanently change the characteristics of waste;
Process must facilitate the waste's handling or recovery.

Based on the Environment Agency (2006); the three main methods of waste processing are chemical, biological and physical. Each of the processes comprise of many technologies as shown below:

Biological: focusing on aerobic (with air) or anaerobic (without air) waste processing techniques.

Chemical: study on pyrolysis, incineration and gasification technologies.

Physical: studies of waste processing plants that use autoclaving and thermo-treatment techniques.

However, biological processes have become popular among other technologies and gained an interest in the field of waste treatment. These treatment technologies can maximize the recycling and recovery of waste components. The description details of its benefits are explained in the section below.

Table 2.2 Disposal methods of MSW in Asia and Pacific region countries

Country	Disposal methods				
	Open burning	Composting	Landfilling	Incineration	Others
Japan	0	10	15	75	0
Singapore	0	0	30	70	0
Australia	0	10	80	5	5
Republic of Korea	20	5	60	5	10
Malaysia	50	10	30	5	5
Indonesia	60	15	10	2	13
Philippines	75	10	10	0	5
Vietnam	70	10	0	0	20
Pakistan	80	5	5	0	10
Bangladesh	95	0	0	0	5
Nepal	70	5	10	0	15
Mongolia	85	5	0	0	10

Source: UN, 2000 cited in Visvanathan et al., 2004

2.6.1 Aerobic composting

Composting is the process of converting organic residues of plant and animal origin into manure, rich in humus and plant nutrients. Mostly, it is the microbial process (Khanna et al., 1995). Composting can be applied to various kinds of waste including: yard waste, separated MSW, and commingled waste. However, SCTD (2003) reported that as management practices, more care should be taken on selecting suitable materials for composting. In most systems, 98% of the biodegradable can be composted without much problem. But in urban areas, as there are space limitations, any form of malfunction in the composting process can lead to environmental issues in the surroundings. Malfunctions are caused primarily when non-degradable materials are added to the composting process. The below Table 2.3 illustrates the detailed of waste type suitable for composting.

Recently, biological waste treatment methods have prepared the way for recycling the organics compounds and nutrients from the organic fraction of MSW. Aerobic composting is called an energy consuming process because around 30-35 kWh is consumed by one ton of feedstock (Braber, 1995; Hartmann & Ahring, 2006). Furthermore, composting has a negative environmental impact due to considerable CH_4 emission into the atmosphere (Edelmann et al., 2000 cited in Hartmann & Ahring, 2006). Therefore, it is not the attractive method in terms of its economical value as well as environmental conservation. Moreover, the composting of OFMSW as the feedstock is not marketable due to heavy metals contamination and trace amounts of household hazardous wastes. So source separated material is recommended for use as feedstock to produce the highest quality of compost. Interestingly, Brinton (2000) highlights that bio-waste compost contained on average 1/4 the metals content of non separated source MSW composts.

Table 2.3 Waste components to be composted and excluded from composting

Materials to include	Materials to exclude
Vegetables/kitchen refuses	Non biodegradable waste: polythene, Plastics, glass, metal, etc.
Garden trimmings, grass clippings	Human faeces, pet manure(e.g. dog, cat)
Leaves, dry leaves (straw)	Dairy Products
Twigs and shredded branches	Diseased plants
Food refuses :bread, buns etc	Fish , meat scraps and bones
Egg shells	Slow degradable materials like coconut shells, coconut husk, etc.
Farm animal manure (e.g. Cow, Sheep, Goat , Poultry)	Fats/cooking oils
Fruit refuses	Hazardous material like batteries, bulbs, electronic components, chemicals
Wood ash	

Source: SCTD, 2003

2.6.2 Anaerobic digestion

Among biological treatments, AD frequently the most cost effective owing to the high energy recovery linked to the process and its limited environmental impacts, especially considering its limited greenhouse gases effect (Mata Alvarez, 2003). The literature bears evidences for anaerobic treatment of solid waste to be becoming popular in this regard. It is a self driven process in nature, to enhance both good quality and higher biogas yield at shorter reaction time. AD can be the attractive method for both energy generation and waste disposal (Rao & Singh, 2004). AD has the advantage over composting, incineration or combination of digestion and composting, mainly because AD improved energy balances. In conclusion, AD will become much more important in the future for ecological reasons. As stated by Mata Alvarez (2003); the future of AD should be sought in the context of an overall sustainable waste management perspective. In terms of global warming, AD scores much better than other options as can be seen in Table 2.4. It illustrate that there is no any greenhouse gas emission from anerobic treatment process. There are a number of benefits resulting from the use of AD technology which is summarized in the Table 2.5.

Besides to those advantages, there are also problems arising from this system (WD, 2006) as the following:

It is a slower process than aerobic digestion
It is more sensitive to upsets by toxicants
Start-up of the process requires long periods of time
Regarding biodegradation of xenobiotic compounds by co metabolism, anaerobic processes require relatively high concentrations of primary substrates

However, it is difficult to discuss in detail the economics of implementing an Anaerobic Digestion Plant for MSW, because of many factors that affect the costs and the variation in circumstances and costs between different countries. For example, RISE-AT (1998) highlight that the following factors will have an influence on the overall treatment costs:

Energy Prices
Energy Taxes & Renewable Energy Policy
Land Prices
Labor Costs
Construction and material costs
Markets for the compost/soil conditioning product and prices
Quality of the compost produced

Table 2.4 Contribution of the different greenhouse gases and different sources of methane emission

Source	Contribution (%)	Reference
Energy production	26	IPPC (1994)
	28	IPPC (1992)
Enteric fermentation	24	IPPC (1994)
	23	IPPC (1992)
Rice cultivation	17	IPPC (1994)
	21	IPPC (1992)
Wastes	7	IPPC (1994)
	17	IPPC (1992)
Landfill	11	IPPC (1994)
	-	IPPC (1992)
Biomass burning	8	IPPC (1994)
	11	IPPC (1992)
Urban wastewater	7	IPPC (1994)
	-	IPPC (1992)
CO_2	65	IPPC (1996)
	66	USEPA (1993)
CH_4	20	IPPC (1996)
	18	USEPA (1993)
CFCs	10	IPPC (1996)
	11	USEPA (1993)
N_2O	5	IPPC (1996)
	5	USEPA (1993)

Source: Mata-Avarez, 2003

2.7 Concepts of anaerobic digestion

Generally, the overall AD process can be divided into four stages: Pretreatment, waste digestion, gas recovery and residue treatment (Buvet et al., 1980; IEA, 2001). Figure 2.4 show the overall process of anaerobic digestion.

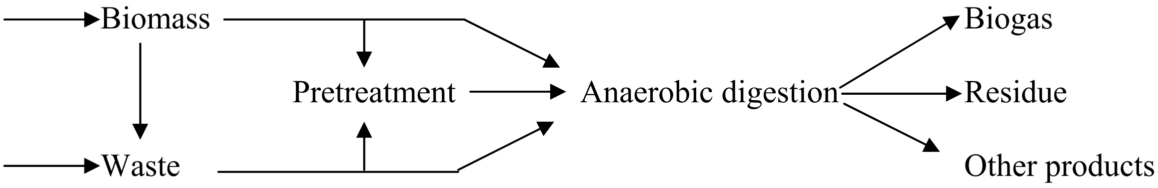

Figure 2.4 Overall process of anaerobic technology

Table 2.5 Benefits gained from anaerobic digestion process

Waste treatment technology Natural waste treatment process Requires less land than aerobic composting or landfilling Reduces disposed waste volume and weight to be landfilled	**Energy benefits** Net energy producing process Generate high quality renewable fuel Biogas proven in numerous end-use applications
Environmental benefits Significantly reduces carbon dioxide and methane emissions Eliminates odors Produces a sanitized compost and nutrient-rich liquid fertilizer Maximizes recycling benefits	**Economic benefits:** is more cost-effective than other treatment options from a life-cycle perspective

Source: IEA, 2001

2.7.1 Pretreatment

AD has proven to be the most beneficial stabilization technique for its volume reducing capabilities and ability to create energy in the form of methane gas. This process becomes efficient when the feedstock is pretreated before loading in to the reactor (White, 1997). Most digestion systems require pretreatment of waste to obtain homogeneous feedstock. The pretreatment processing involves separation of non-digestible materials and shredding. The waste received by the AD reactor is usually source separated or mechanically sorted. The separation ensures removal of undesirable or recyclable materials (Verma, 2002). Having separated any recyclable or unwanted materials from waste, the organic material must be chopped or shredded before it is fed into the digester. The organic matter is also diluted with a liquid, ranging from sewage slurry, to recycled water from the process. In some systems, an aerobic pretreatment allows organic matter to be partly decomposed under aerobic conditions before undergoing anaerobic digestion (RISE-AT, 1998). However, the loss of biogas is the drawback from the aerobic composting pretreatment (Brummeler & Koster, 1990). Nevertheless, conducting anaerobic digestion of untreated sludge, results in the destruction of approximately 40 percent of volatile organics to methane and carbon dioxide gas. In contrast, pretreated sludge achieves 75 percent destruction rate of volatile organics, resulting in a greater production of CH_4 gas. Their study also concluded that the pretreatment process was both technically feasible and economically competitive with other present pretreatment processes (White, 1997).

2.7.2 Anaerobic Digestion process

Anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. Table 2.6 depicts in detail the types of microorganisms and populations involved in anaerobic digester. It is the consequence of a series of metabolic interactions among various groups of microorganisms

AD is a series of chemical reactions during which organic material is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen depleted environment. AD can be used to process any carbon-containing material, including food, paper, sewage, yard trimmings and solid waste, with varying degrees of degradation. The OFMSW, for example, is a complex substrate that requires an intricate series of metabolic reactions to be degraded (Ostrem, 2004). This section describes these reactions detailing the intermediary products produced and the bacteria involved. The full process can be considered to occur in four stages as illustrated in Figure 2.5, hydrolysis, in which complex molecules are broken down to constituent monomers; acidogenesis, in which acids are formed; acetogenesis, or the production of acetate; and methanogenesis, the stage in which methane is produced from either acetate or hydrogen. Digestion is not complete until the substrate has undergone all of these stages, each of which has a physiologically unique bacteria population responsible that requires disparate environmental conditions.

Table 2.6 Bacterial population from anaerobic digester

Group	Cell/mL
Total hydrolytic bacteria	10^8-10^9
Proteolytic	10^7
Cellulolytic	10^5
Hemicellulolytic	10^6-10^7
Hydrogen-producing acetogenic Bacteria	10^8-10^9
Homoacetogenic bacteria	10^6
Methanogens	10^5-10^6
Sulphate reducers	10^4

Source: Khanna et al., 1995

a. Hydrolysis/liquefaction

In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes as shown in Figure 2.6. The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. In general, hydrolysis is the rate limiting step if the substrate is in particulate form. The rate of hydrolysis is a function of factors such as pH, temperature, composition and particle size of substrate, and high concentration of intermediate products

(Veeken, et al., 2000). Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provides a higher CH_4 yield (Verma, 2002). In some processes, this initial step is catalyzed by the use of an acid or alkali. In some industrial processes, hydrolysis process is added at the beginning stage to substantially degrade the hydrocarbon content of the solid waste before it is added to the digester. This provides a higher CH_4 yield and gives a shorter digestion time. It also reduces the thick fibrous scum that can form on top of the digesting mixture and generally makes it less viscous and easier to process (RISE-AT, 1998). The degradation of complex polymeric substances found in solid waste includes lingocellulose, proteins, lipids and starch. In general MSW contains 40-50% of cellulose, 12% of hemicellulose and 10-15% of lignin by dry weight (Wang, et al., 1994). Carbohydrates, on the other hand, are known to be more rapidly converted via hydrolysis to simple sugars and subsequently fermented to volatile fatty acids (Mata-Alvarez, 2003).

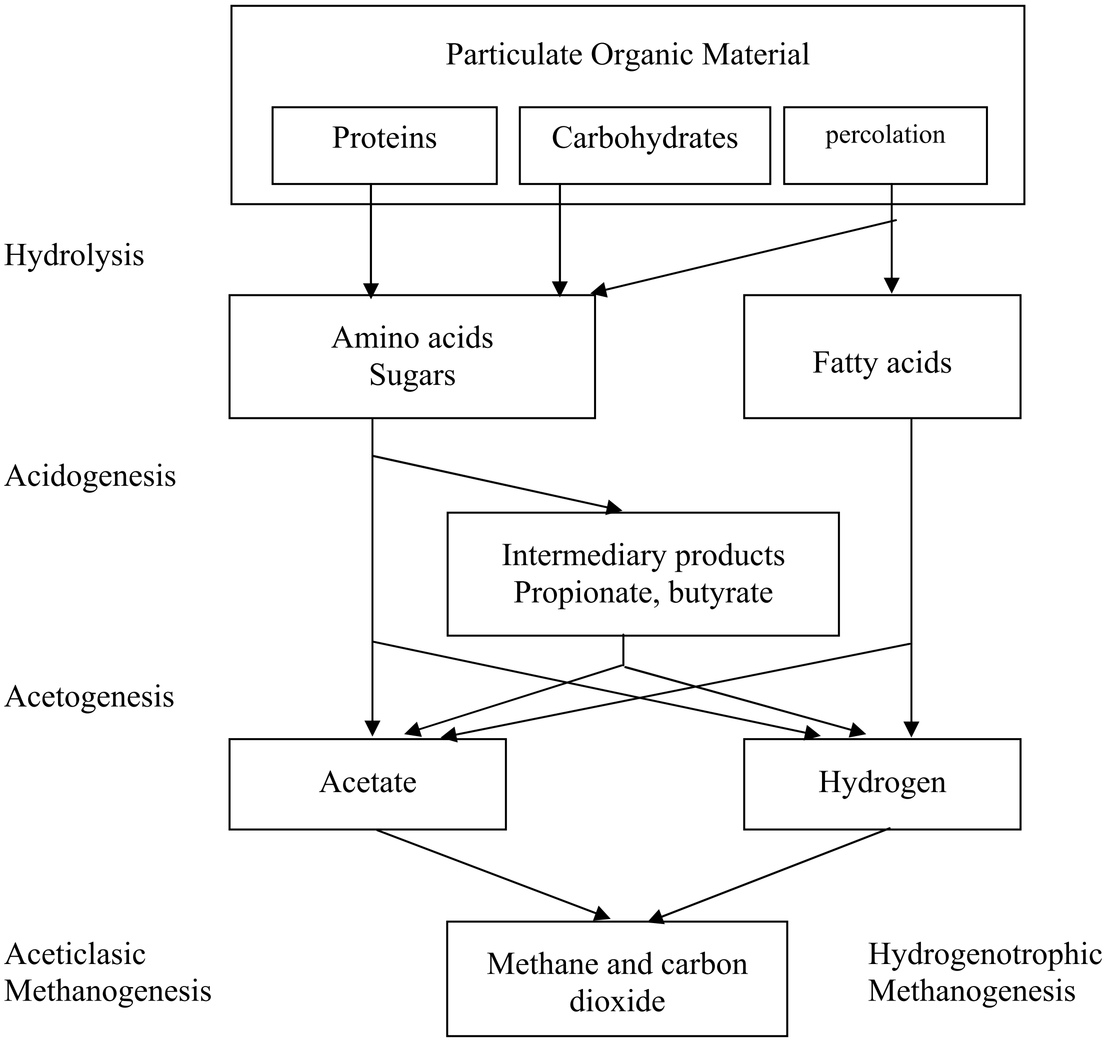

Figure 2.5 Breakdown of organic matter by anaerobes (Mata Alvarez, 2003)

Lipids → Fatty Acids
Polysaccharides → Monosaccharides

$$\text{Protein} \longrightarrow \text{Amino Acids}$$

Figure 2.6: Illustration of hydrolysis reaction

b. Acidogenesis

Soluble organic components including the products of hydrolysis are converted into organic acids, alcohol, hydrogen, and carbon dioxide by the action of acid forming bacteria known as acidogens (Figure 2.7)

$$\text{Soluble organic} \left\{ \begin{array}{l} \text{Amino acid} \\ \text{Monossacharide} \\ \text{Fatty acids} \end{array} \right\} \xrightarrow{\text{Acidogens}} \left\{ \begin{array}{l} \text{Intermediate products} \\ \text{(Propionate, butyrate,} \\ \text{alcohol, etc.)} \end{array} \right\}$$

Figure 2.7 Illustration of acidogenesis reaction

c. Acetogenesis

The simple monomer blocks formed in hydrolysis act as substrate feedstock for the fermenting, acid forming anaerobic bacteria. It may be difficult to distinguish this stage from the previous one for some molecules which will be absorbed without further break down and can be degraded internally (Meynell, 1982). Acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen as illustrated in Figure 2.8. The principal acids produced are: acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). The products formed during acetogenesis are due to a number of different microbes, e.g., s*yntrophobacter wolinii*, a propionate decomposer and s*ytrophomonos wolfei*, a butyrate decomposer. Other acid formers are *clostridium species, peptococcus anerobus, lactobacillus*, and *actinomyces* (Verma, 2002).

$$\begin{array}{c} \text{Intermediate products} \\ \text{(Propionate, butyreate, alcohol, etc.)} \end{array} \xrightarrow{\text{Acetogens}} \begin{array}{l} \text{Acetate, carbon dioxide} \\ \text{and hydrgen} \end{array}$$

Figure 2.8 Illustration of acetogenesis reaction

When the digester becomes too acidic, this means acid forming bacteria is producing faster than the methane formers. The "acid formers" produce too much acid for the "methane formers" to digest, causing the imbalance condition, which means that a high acidic condition exists. This sours the digester and prevents the formation of methane gas. One method to correct this situation is to add sodium bicarbonate into the digester. This counteracts the acid and brings the balance back to normal (NFEC, 1999).

d. Methanogenesis

Finally, in the third stage, methane is produced by bacteria called methane formers (also known as methanogens) in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methanogenic bacteria are highly sensitive to oxygen concentration in the system, resulting in an inactive phase in the system as well as a high concentration of fatty acids in the environment (Sharma et al., 2000). Consequently, the pH value will be lower.

Methane production is higher from the reduction of carbon dioxide but limited hydrogen concentration in digesters results in an acetate reaction, which is the primary producer of methane. The 4 methanogenic bacteria include *methanobacterium, methanobacillus, methanococcus and methanosarcina*. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. Methanosarcina species and methanothrix species or methanosaeta; are considered to be important in AD both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$CH_3COOH \longrightarrow CH_4 + CO_2$$

$$2C_2H_5OH + CO_2 \longrightarrow CH_4 + 2CH_3COOH$$

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$$

About two thirds of methane is derived from acetate conversion by methanogens. The other is the result of carbon dioxide reduction by hydrogen (WD, 2006). Although AD can be considered to take place in these four stages, all processes occur simultaneously and synergistically, in as much as the first group has to perform its metabolic action before the next can take over, and so forth (Ostrem, 2004).

2.7.3 System parameters

The digester performances are determined by system parameters. These indicators are based on gas production, destruction of volatile solid matters, alkalinity, volatile acid content and pH. Some of the parameters are described below.

a. Gas production

The gas is produced as a result of breakdown of organic material. Thus the volume of gas produced is an indication of high rate of breakdown of the substrate in the reactor which was utilized by microorganisms.

b. Volatile solid destruction

The destruction is limited to organic matter since digestion is a biological process. The net change or loss in volatile solid is a measure of decomposition. It is the different between the volatile matter of substrate fed and solid residue remain after digestion at some period of time. The actual breakdown of organic material is higher than that is indicated by the loss, since a portion of organic matter is converted into microbial cellular. The loss is in the form of CO_2 and CH_4 of complete degradation occurs. Otherwise, the loss is in the form of an intermediate compound such as VFA if the degradation is incompleted.

2.7.4 AD products

a. Biogas recovery

Biogas is formed by the activity of anaerobic bacteria. Microbial growth and biogas production are very slow at ambient temperatures. These bacteria occur naturally in organic environments where oxygen is limited. Biogas is comprised of methane (60%), carbon dioxide (40%) and hydrogen sulfide (0.2 to 0.4%) as shown in Table 2.7. Biogas is very corrosive to equipment and requires frequent oil changes in an engine generator set to prevent mechanical failure. The heating value of biogas is about 60% of natural gas and about 1/4 of propane (IEA, 2001). Angelidaki et al. (2006) reported that the maximum methane yield (0.43 m^3/kg VS) and the best degradation rate for OFMSW could be obtained from batch experiment at low TS content (1.5%) and under thermoplilic conditions.

The gas produced contains methane, carbon dioxide, some inert gases and sulphur compounds. Typically 100-200 m^3 of gas is produced per ton of organic MSW that is digested.

Table 2.7 Typical Biogas composition

Type of gas and energy	Quantity
Methane	55-70% by volume
Carbon dioxide	30-45% by volume
Hydrogen Sulphide	200-4000 ppm by volume
Energy Content	20-25 MJ/m^3

Source: RISE-AT, 1998

b. Digestate and its post treatment

The residues after the digestion process provide two useful products: a solid material termed digestate and liquid material. The digestate leaving the reactors is a thick sludge with a moisture content of about 80%. To transport this would be uneconomic, and so digestate is normally dewatered. The solid is reduced to a liquid content of about 50% - 70% and the remaining water can be collected. The smell of fresh digestate is unpleasant, and coupled with the malodorous characteristics of putrescible waste. The quality and composition of the dewatered solid depend on the feedstock and the digestion process. Only soluble organics are degraded in the digester, so other materials, such as glass or plastics, or trace elements, such as heavy metals or salts, will be present in the solid if they entered in the feedstock. The safety of the digestate, measured by the concentration of pathogens present, is of great concern of end users. Pathogen destruction can be guaranteed at thermophilic temperatures with a high SRT (Solid Retention Time) (RI International, 2002). The digestate will be used as a soil amendment; a biologically active solid is beneficial.

Many AD facilities post-treat the digestate aerobically, in a process known as curing, in order to produce high quality compost. AD does not reduce Nitrogen, Phosphorus and Potassium (NPK) content, making the digestate more valuable as a fertilizer (Ostrem, 2004). Nevertheless, Rao & Singh (2004) reported that the low C/N weight ratio (15:1) in digested substrate indicates that it can be used as a bio-fertilizer or soil conditioner from the earlier statements. The liquid fraction contains about two thirds of the nutrients in the wastes and can be used as a fertilizer sprayed onto crops. Where digesters are linked to farms, as in Continuous Anaerobic Digestion (CAD) plants, it is common for the liquid and solid not to be separated and the slurry to be spread on the land. This save costs in the dewatering process. The key factor that has to be controlled is the quality of the digestate. The main aspects that need to be controlled are the chemical, physical and biological properties. These qualities are controlled through controlling the feedstock, optimizing the process and finally management of the final digestate (IEA, 2001).

Compost from digestate is produced at many AD sites in Europe, but without research addressing its safety and benefits in comparison to other compost, the degree of market penetration will be minimal. When this is established, AD can also be seen as an integral part of the disease management system in agriculture as well as urban settings. Compost can also reduce the need for artificial fertilizers, which are derived from natural gas, result in water contamination, and deplete soil health. The quantifiable benefits of displacing artificial fertilizer include reducing the significant CO_2 emissions associated with their manufacture, and reducing the N_2O emissions released through their use.

The liquid remaining from the dewatering process can be used in three ways (RI International, 2002). Least advantageously, it can be discharged as sewage to a wastewater treatment plant, as it is too active to be discharged directly to fresh water. It can also be recycled in the process for waste pretreatment or to adjust the moisture content in the digester. Finally, it can be sold as a liquid fertilizer. Because nutrients are present in the liquid, this option is attractive. The logistics of transporting high quantities of water, however, usually make this option prohibitively expensive except where AD is used on farms.

As post-treatment steps, the typical sequence involves mechanical dewatering, aerobic maturation, and water treatment but possible alternatives exist such as biological dewatering or wet mechanical separation schemes in which various products may be recovered (Vandevivere et al., 1999). Overall, Table 2.8 shows the possible unit processes, products and quality standards in AD for organic solid wastes.

2.8 Energy Displacement Impacts

Anaerobic digestion is a net energy-producing process. The plant electrical and heat requirement is about 22% of the energy produced for dry processes, with 78% available for export as either a natural gas substitute or as other forms. In the case of wet anaerobic processes, the parasitic load is about 37% of plant production, with 63% of plant energy production available for export. The higher plant energy requirement for the wet process is related to the need to heat large amounts of water in the digesters. Estimating the potential value of surplus energy is dependent on a wide range of variables. Factors that influence energy production include: Feedstock selection, Plant operation, and Local market conditions (RIS international, 2002).

Generally, there are four options for using excess energy from AD plants:

Clean the biogas to extract the methane gas, which can then be exported off-site and sold as a substitute for natural gas;

Burn the methane gas in an internal combustion engine to produce electricity for sale off site while collecting heat from the engine's exhaust and cooling system to produce steam or hot water;

Burn the methane gas in a boiler to produce steam for use onsite and sale off-site, or

Convert methane gas into compressed natural gas (CNG) for use as a fuel source for light and heavy-duty vehicles. Vehicles powered by CNG, such as municipal buses, offer a number of positive environmental benefits including reduced noise levels and cleaner emissions compared to diesel-powered vehicles. Operators of CNG-powered vehicles have reported that vehicle maintenance costs are 40-50% lower than diesel fuel.

Other benefits include the reduced demand for new power generating facilities and the displacement of environmental impacts associated with their construction.

Table 2.8 Possible unit processes, products and quality standards involved in an anaerobic digestion plant for organics solids.

Unit process	Reusable products	Standards or criteria
Pretreatment - Magnetic separation - Size reduction (Drum or shredder) - Pulping with gravity separation - Drum screening - Pasteurization	- Ferrous metal - Heavy inerts reused as construction material - Coarse fraction, plastics	- Organic impurities - Comminution of paper, cardboard and bags - Organic impurities - Calorific value - Seed exterminates
Digestion - Hydrolysis - Methanogenesis - Biogas valorization	-Biogas - Electricity, Heat (steam)	- Norms nitrogen, sulfur - 150 - 300 kW.h.of electricity /ton - 250 - 500 kW.h. of heat/ton
Post treatment - Mechanical dewatering - Aerobic stabilization or biological dewatering - Water treatment - Biological dewatering - Wet separation	- Compost - Water - Compost - Sand, Fibres (peat), Sludge	- Load on water treatment - Norms soil amendments - Disposal norms - Norms soil amendments - Organic impurities, Norms potting media, Calorific value

Source: Vandevivere et al., 1999

2.9 Factors affecting AD Process

The rate at which the microorganisms grow is of paramount 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 anaerobic digestion may comprise of biodegradable organic fraction, combustible and inert fraction. The biodegradable organic fraction includes kitchen scraps, food residues, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocelluloses organic matter containing coarser wood, paper, and cardboard. Organic material, such as fats, carbohydrates and proteins, is the main source of nutrient for bacteria involved in the first stage of the process called hydrolysis (Stafford et al., 1980). If those materials are present in the anaerobic plant feedstock, the possible gas production can be estimated. However, lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the Refractory Volatile Solids (RVS) in organic MSW. Waste characterized by high VS and low non-biodegradable matter, or RVS, is best suited to AD treatment. The composition of wastes affects the yield and biogas quality as well as the compost quality (Verma, 2002).

2.9.2 Alkalinity and pH Level

pH is the convenient measure of how acid or alkali the liquid is. Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. Moreover, it is also sensitive to high oxygen concentrations (Sharma et al., 2000). It has been determined by RISE-AT (1998) that an optimum pH value for AD lies between 5.5 and 8.5. 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, and in a batch reactor, acetogenesis occurs at a rapid pace. Acetogenesis 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. Moreover, Chen et al. (1996) stated that at a pH between 6.4-6.9, the methanogens remained inactive. Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once CH_4 production is stabilized, the pH level stays between 7.2 and 8.2.

2.9.3 Temperature

AD can take place at any temperature (5°C-55°C) ranging from psychrophilic temperature to some extreme thermophilic. There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic range which operates best between 5-40°C, and the thermophilic range which lies between 50°C-65°C (RISE-AT, 1998; Meynell, 1982). It has been observed that higher temperatures in the thermophilic range reduce the required retention time. In fact, the greater gas production can be obtained if a digester operates in thermoplilic condition as shown in Figure 2.9. However, it is rarely done because the energy requirement in maintaining the temperature is more expensive than the biogas yields. Moreover, the thermoplilic bacteria are more sensitive than that mesoplilic bacteria, so higher costs are needed to control the temperature in the thermophilic range (Meynell, 1982). Thus, a mesophilic digester must be designed to operate at temperatures between 30°C and 35°C for its optimal functioning (WD, 2006).

2.9.4 Carbon to Nitrogen Ratio (C/N)

With regard to chemical composition of substrate and feed, elemental composition and the structure of the molecules that contain essential elements are main considerations. Macronutrients include Nitrogen, Phosphorus, and Potassium ("NPK"). Not only are these elements essential, they must also be present in an appropriate ratio, i.e., a certain balance must exist between the three elements. An appropriate carbon-to-nitrogen ratio (C:N) is a requisite for the continued successful functioning of a digester. An excessively high C:N promotes acid formation and accumulation. The accumulation retards methanogenesis activity and, hence, methane production ceases. On the other hand, when the C:N is too low, nitrogen is converted to ammonium-N at a faster rate than can be assimilated by the methanogens. As a consequence, ammonia reaches concentrations that are toxic to the microbes (Mata-Alvarez, 2000).

Nutrient deficiencies in the waste are remedied either by adding a waste that contains the missing nutrients, or by enriching the deficient substrate with appropriate chemical fertilizer elements. The monetary costs of chemical fertilizer elements usually discourage their use in developing countries.

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20-30. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in a 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 (Vema, 2002). The various range of C/N ratio of different kinds of substances is shown in the Table 2.9.

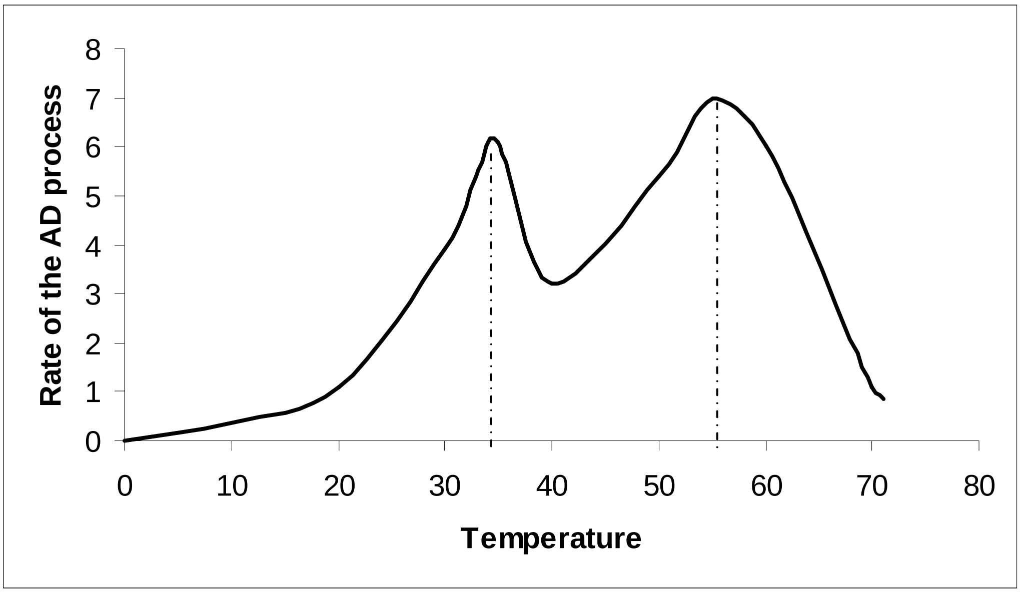

Figure 2.9 Temperature range for anaerobic digestion (Mata Alvarez, 2003)

2.9.5 Total solids content (TS)/ Organic Loading Rate (OLR)

As discussed earlier, Low solids (LS) AD systems contain less than 10% TS, medium solids (MS) about 15-20% and high solids (HS) processes range from 22% to 40% (Tchobanoglous, et al., 1993). An increase in TS in the reactor results in a corresponding decrease in the reactor volume. Organic loading rate (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 (Vandevivere, 1999). In such 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). Both biogas yield and CH_4 production have a close relation with Organic Loading Rate (ORL), so special emphasis should be made on reactor performance at steady state condition on the OLR that does not result in reactor failure (Linke, 2006).

2.9.6 Retention Time (RT)

Retention time of anaerobic processes is estimated by dividing the total capacity of the digestion tank by the rate at which organic matter is fed (Meynell, 1982). 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 digesters range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilc range. A high solids reactor operating in the thermophilic range has a retention time of 14 days (Verma, 2002).

Table 2.9 C/N Ratio of some 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	>20

Source: RISE-AT, 1998

2.9.7 Mixing

The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. 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 slow mixing can also be provided by leachate percolation. The objectives of mixing are to combine the fresh material with the bacteria, to stop the formation of scum and to avoid pronounced temperature gradients within the digester (RISE-AT, 1998).

2.9.8 Toxic material

A wide range of toxicants is responsible for the occasional failure of anaerobic digesters. Inhibition of methanogenesis is generally indicated by reduced methane production and increased concentration of volatile acids (WD, 2006). Biomethanogenesis is sensitive to several groups as shown in table 2.10. There is no general agreement on threshold limits for those toxicants. The toxicity effect of inhibitory is depends upon on its concentration and ability of the bacteria to acclimatize to its effects as well as environmental conditions; that is, pH, and temperature (Mata-Avarez, 2003).

2.10 Various AD systems

AD processes can be classified according to the total solids (TS) content of the slurry in the digester reactor. Low solids systems (LS) contain less than 10% TS, medium solids (MS) contain about 15%-20%, and high solids (HS) processes range from 22% to 40% (Tchobanoglous, 1993). AD processes can be categorized further on the basis of number of reactors used, into single-stage and multi-stage. In single stage processes, the three stages of anaerobic process occur in one reactor and are separated in time (i.e., one stage after the other) while multi-stage processes make use of two or more reactors that separate the acetogenesis and methanogenesis stages in space. Batch reactors are used where the reactor is loaded with feedstock at the beginning of the reaction and products are discharged at the end of a cycle. The other type of reactor used, mostly for low solids slurries, is continuous flow where the feedstock is continuously charged and discharged.

Table 2.10 Concentration of inhibitors in anaerobic digestion

Inhibitor	Concentration (mg/L)
Volatile acids	>2,000 (as acetic acids)[a]
Ammonia nitrogen	1,500-3,000 (at pH>7.6)
Sulfide (soluble)[b]	>200; >300 (toxic)
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
Copper	0.5 (soluble metal)
Cadmium	150[c]
Iron	1,710[c]
Cr^{+6}	3
Cr^{+3}	500
Nickel	2[d]

Source: Polprasert, 1996

[a] within the pH range 6.6-7.4, and with adequate buffering capacity, volatile acids concentration of 6,000-8,000 mg/L may be tolerated

[b] off gas concentration of 6 % is toxic

[c] Millimol of metal per kg of dry solids

[d] Nickel promotes methane formation at low concentration. It is required by methanogens

2.10.1 Wet or Dry

AD processes can be classified according to the total solids (TS) content of the slurry in the digester reactor (Tchobanoglous, 1993).

> ***Wet:*** The MSW feedstock is slurried with a large amount of water to provide a dilute feedstock of 10-15% dry solids. The drawback of wet process or low solid is the large amount of water used, resulting in high reactor volume and expensive post-treatment technology. The expensive post treatment is due to dewatering required at the end of the digestion process.
>
> ***Dry:*** The feedstock used has a dry solids content of 20-40%. High solid systems require a smaller reactor volume per unit of production but this is counterbalanced by the more expensive equipment (pumps, etc.) required. Technically, high solid reactors are more robust and have high organic loading rates. Most AD plants built in the 80's were predominantly low solids but during the last decade the number of high solids processes has increased appreciably. There is substantial indication from the obtained data that high solids plants are emerging as winners.

2.10.2 Batch or Continuous

Based on the mode of operation, it can be classified into two processes:

> ***Batch:*** The reactor vessel is loaded with raw feedstock and inoculated with digestate from another reactor. It is then sealed and left until thorough degradation has occurred. The digester is then emptied and a new batch of organic mixture is added. The sequencing batch concept is generally similar to dry batch digestion, except that leachate from the base of the vessel is exchanged between established and new batches to facilitate start up, inoculation and removal of volatile materials in the active reactor. After the digestion process becomes established in the solid waste, the digester is uncoupled and reconnected to a fresh batch of MSW in a second vessel.
>
> ***Continuous:*** The reactor vessel is fed continuously with digestate material; fully degraded material is continuously removed from the bottom of the reactor. This concept involves a continuously-fed digestion vessel with a digestate dry matter content of 20-40 %. Both completely-mixed and plug-flow systems are available. Plug flow systems rely on external recycle of a proportion of the outgoing digestate to inoculate the incoming raw feedstock. In both cases, the requirement for only minimal water additions makes the overall heat balance favorable for operation at thermophilic digestion temperatures (50-55°C).

2.10.3 Single Step/Multi-Step

AD processes can be categorized further on the basis of number of reactors used, into single-stage and multi-stage

Single Step: All digestion occurs in one reactor vessel. The technical drawback of the complete mix reactor is the occurrence of short-circuiting, i.e. the passage of a fraction of the feed through the reactor with a shorter retention time than the average retention time of the bulk stream. Not only does short-circuiting diminish the biogas yield, most importantly it impairs the proper hygienization of the wastes, i.e. the kill-off of microbial pathogens which requires a minimum retention time to complete.

Multi-Step: Process consists of several reactors; often the organic acid forming stage of the anaerobic digestion process (acetogenesis) is separated from the methane forming stage (methanogenesis). This results in an increased efficiency as the two microorganisms are separate in terms of nutrient needs, growth capacity and the ability to cope with environmental stress. Some multistage systems also use a preliminary aerobic stage to raise the temperature and increase the degradation of the organic material. In other systems the reactors are separated into a mesophilic stage and a thermophilic stage. However, Table 2.11 describes the advantages and disadvantages of the one and two stage systems.

2.10.4 Co-digestion/ Digestion of MSW alone

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

Co-digestion: 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 the gas production. A recent study conducted by Lopes et al. (2004) confirmed that the addition of inoculum (sludges and animal manure) could improve the performance of the process. Therefore, co-digestion is an interesting part of the process to be investigated on various substrates.

2.11 Continuous anaerobic digester

The principal objective of developing a continuous AD digestion was to achieve a low initial investment, high efficiency and relatively simple operational and maintenance requirement. The reactor vessel is fed continuously with digestate material; fully degraded material is continuously removed from the bottom of the reactor (RISE-AT, 1998). However, due to technical problems associated with the pump, feeding the reactor continuously was not possible (Shama et al., 2000).

However, based on RISE-AT 1998 report, the current leading continuous anaerobic plants are:

***Dry Continuous Digestion**:* Continuously fed vessel with dry digestate matter content of 20-40%. Minimal water addition makes the overall heat balance very favorable for operation at thermophilic temperatures.

***Wet Continuous Single-Step Digestion**:* MSW feedstock is slurried with a large amount of water (10% solids). The system leads itself to co-digestion of MSW with more dilute feedstock such as sewage sludge or animal manure. Effective removal of glass and stones is required to prevent rapid accumulation of these in the bottom of the reactor. The digestate requires dewatering to recover liquid, (which can be recycled to mix with incoming waste), to produce a solid digestate for disposal.

Wet Continuous Multi-Step Digestion: MSW feedstock is slurried with water or recycled liquid (10% solids content) and fed to a series of reactors where acetogenesis occurs in a separate reactor from methanogenesis stage.

Table 2.11 Advantages and disadvantages of one and two-stage systems

Criteria	Advantages	Disadvantages
One stage system (Dry)		
- Technical	- No moving parts inside reactor - Robust (inerts and plastics need no be removed) - No short-circuiting	- Wet wastes (< 20 % TS) cannot b treated alone
- Biological	- Less VS loss in pre- treatment - Larger OLR (high biomass) - Limited dispersion of transient peak concentrations of inhibitors	- Little possibility to dilute inhibitors with fresh water
- Economical & Environmental	- Cheaper pre-treatment and smaller reactors - Complete hygienization - Very small water usage - Smaller heat requirement	- More robust and expensive waste handling equipment (compensated by smaller and simpler reactor)
One stage system (Wet)		
- Technical	- Inspired from known process	- Short-circuiting - Sink and float phases - Abrasion with sand - Complicated pre-treatment
- Biological	- Dilution of inhibitors with fresh water	- Particularly sensitive to shock loads as inhibitors spread immediately in reactor - VS lost with inerts and plastics
- Economical & Environmental	- Equipment to handle slurries is cheaper (compensated by additional pre-treatment steps and large reactor volume)	- High consumption of water - Higher energy consumption for heating large volume
Two stage system		
- Technical	- Design flexibility	- Complex
- Biological	- More reliable for cellulose-poor kitchen waste - Only reliable design (with biomass retention) for C/N < 20	- Smaller biogas yield (when solids not methanogenized
- Economical & Environmental	- Less heavy metal in compost (when solids not methanogenized)	- Larger investment

Source: Vandevivere et al., 1999

Chapter 3

Methodology

3.1 Introduction

As mentioned in chapter 2, various kinds of anaerobic digestion technologies are being developed. However, any kind of reactors design and operational criteria selection to be operated is depends upon the feedstock characteristics, financial aspects etc. Anyhow, each mode of operation always has its own advantages and limitations. However, this research is dealing with continuous mode of digester using an inclined horizontal reactor.

The experiments were conducted in the pilot scale reactor. The solid waste used in this study was collected from Taklong municipality dumpsite, Pathumthani, Thailand. Feedstock, OFMSW, was taken, by manual separation from representative samples. The feedstock was shredded to get substrate with particle size of 10 mm using a mechanical shredder. In addition, operating conditions used in this experiments selected was thermoplilic (55°C). Moreover, active inoculums consisted of cow dung, anaerobic sludge digested waste and matured leachate obtained from previous study of Adhikari (2006) was used in this study.

Biochemical Methane Potential (BMP) test was done for 50 days at 55°C to compare with the pilot scale operation in terms of methane gas production. Solid waste characteristics, nutrient content, heavy metals, biogas and leachate characteristics were analyzed on daily basis. The results obtained both from laboratory and pilot scale experiments were used to compare in terms of biogas production and digestate waste properties. Figure 3.1 represents the methodology of this study.

3.2 Pilot scale horizontal continuous operation

3.2.1 Reactor design and configuration

The experiments were carried out in a pilot scale horizontal reactor. The digester design is illustrated in Figure 3.2. The total volume of digester is approximately 740 L with 616 L of working volume and the rest serving as the available space for biogas generation. The inside diameter of the reactor is 60 cm. The cover plate was attached with a movable screw shaft about at 2 m with piston, and annexed to the upper right side of reactor. At the lower left part, there is the digested waste and the leachate outlet and the screw movable paddle. There is also the water inlet and outlet in order to maintain the thermoplilic conditions in the reactor. There is one gas outlet in this reactor. The reactor was designed as a double wall container, giving the outside space for regulating the temperature of the digester content. Additionally, reactor is well insulated to minimize the heat loss.

The other main equipments for the thermophilic pilot scale experimental set up consist of a leachate tank and lechate pump, temperature controller, thermocouple censor (T-type), heaters, as well as a water jacket.

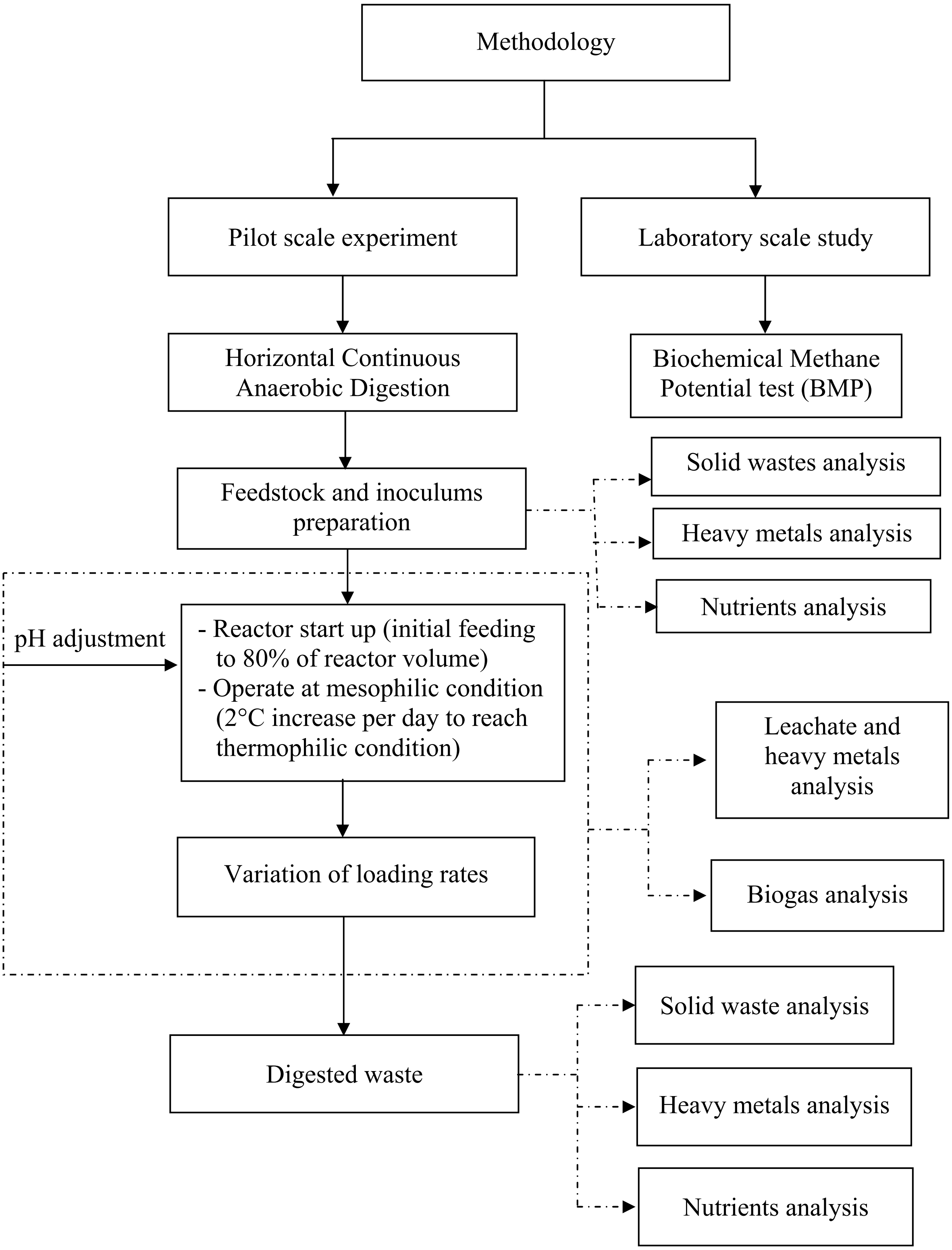

Figure 3.1 Diagram of research methodology

3.2.2 Experimental procedure

a. Feedstock preparation

Solid waste was collected from Taklong municipality dumpsite, in the Pathumthani province of Thailand. None or slow biodegradability wastes such as plastics bags were manually separated, thus it will not hinder the anaerobic digestion process.

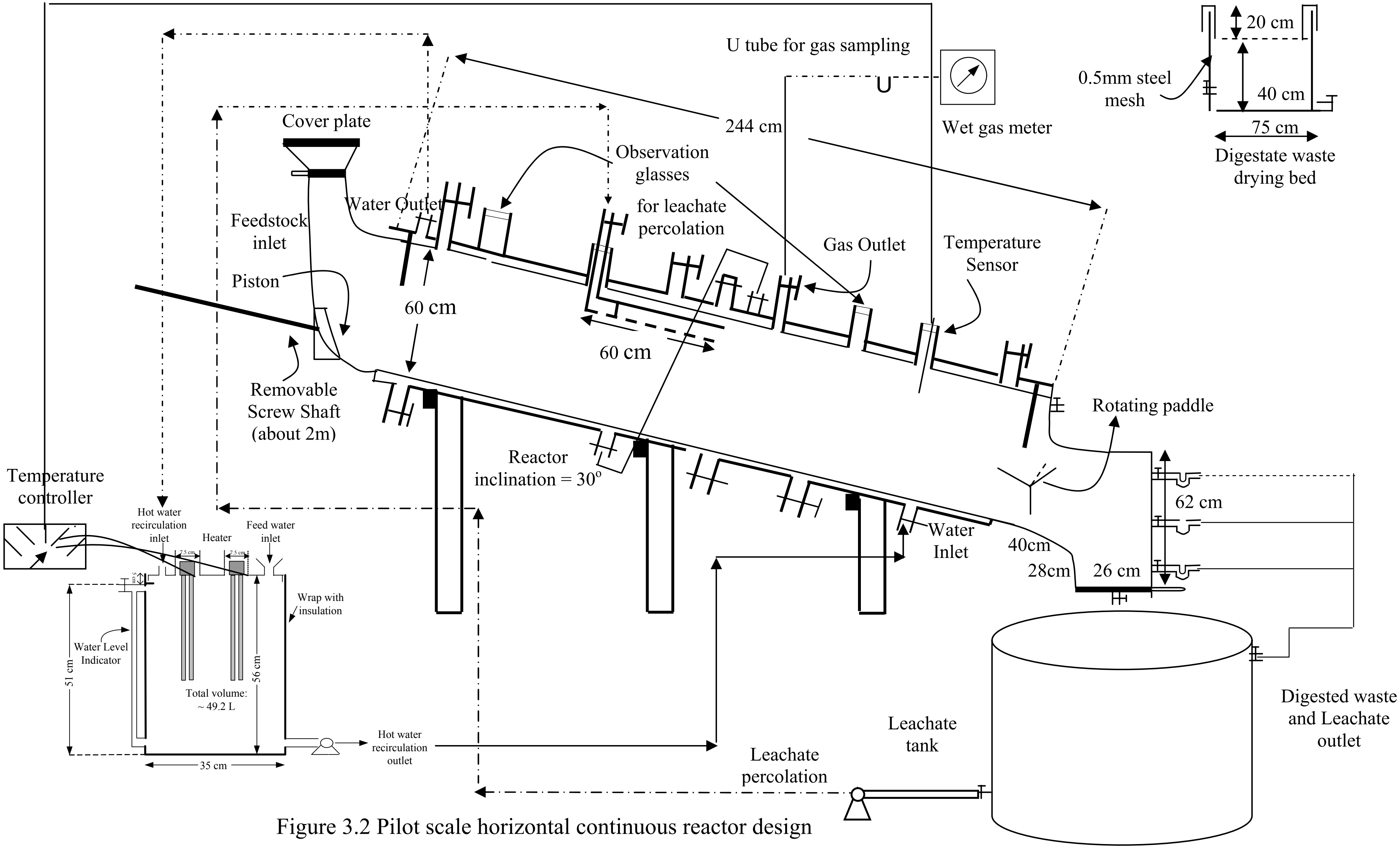

Figure 3.2 Pilot scale horizontal continuous reactor design

Davidsson (2006) reported that the heavy plastic can build up in the reactors, forming a top layer in the digester, which will cause serious problems. Thorough mixing was also needed the get the homogenous biodegradable waste then shredding had to be done to reduce the particle size below 10 mm. This size reduction was able to enhance the hydrolysis capacity due to the larger surface area were available. Feedstock at least enough for three or four weeks was collected and shredded, then stored at 4°C. It was taken out and kept at room temperature for 2-3 hours before feeding into the reactor to avoid thermal shock to microorganisms.

b. Inoculums

The inoculums preparation was based on the previous researchers; Lien (2004), Juanga (2005) and Adhikari (2006) with some modification. The inoculums composition in this study was consisted of cow dung, anaerobic sludge, digested waste, and matured leachate with the proportion of 2:1:1:1. Then, it was mixed with the substrate to start up the process. Moreover, the active inoculum is the main factor to enhance the process efficiency to be mature with a short period of time. It is noted that 20% of inculums (which is 29.6 kg of cow dung, 24.6 L of anaerobic sludge, 14.8 kg of digested waste, and 24.6 L of matured leachate) was mixed well with substrates to start up the reactor.

c. Material balance

In a continuous anaerobic digester, feedstock was continuously added as the amount of digested residues was removed. The schematic diagram of the material balance is shown in Figure 3.3.

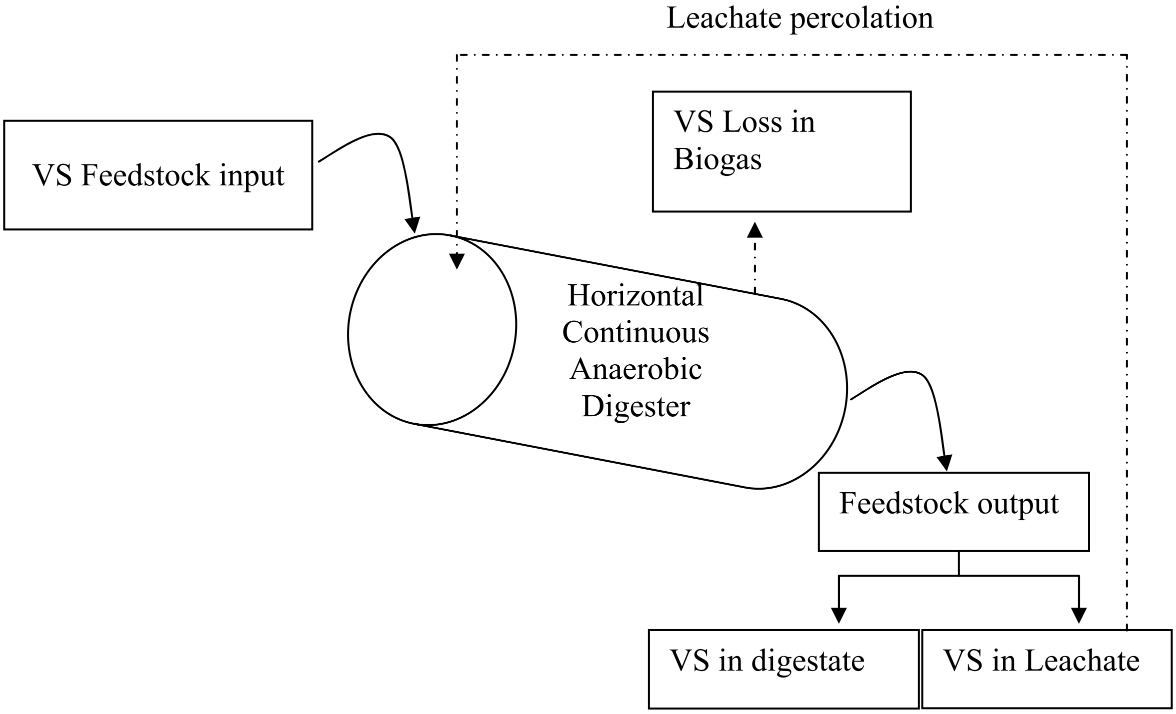

Figure 3.3 Material balance analysis in continuous digester

Solid waste in the reactor consists of solid and liquid phases. During the digestion process, moisture retained in the waste will be converted to leachate and solid fraction will be contributed to biogas production. Mass balance analysis is determined based on the volume of biogas production. From the volumetric point of view, only methane and carbon dioxide are considered, the rest; i.e. the trace gases are neglected (Rao & Singh, 2004). The biogas mass is calculated using the molecular weights of methane (16 g/mol) and carbon dioxide (44 g/mol).The molar volume of ideal gas at Standard Temperature and Pressure (STP) (22.413 L/mol) and normalized individual gas content (vol %) calculated as follows:

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

Where G_m: Biogas mass (g)
V : Biogas volume at STP
CH_4: Normalized methane gas content (vol%)
CO_2: Normalized carbon dioxide gas content (vol%)

Feedstock intake

Assuming that the solid waste comprises of only the solid and liquid phase, Total solids Volatile solid and moisture content of the feedstock intake can be expressed as below:

Total feedstock bulk weight (kg) = X
Moisture content (%) = w
Volatile solid (%) = Z
Total moisture in a given weight of waste (kg) = w × X
Total dry solid present in the waste (TS) (kg) = (1-w) × X
Total volatile solid present in the waste (VS) (kg) = (1-w) × X × Z

Feedstock withdrawal

Similarly, the total digestate bulk weight is assumed to be the mixture of dry digestate and leachate as:

Total bulk digestate withdrawn (kg) = Y
Moiture content (%) = w_1
Volatile solid (%) Z_1
Total moisture content = $w_1 \times Y$
Total dry solid indigestate (TS) (kg) = $(1-w_1) \times Y$
Total Volatile solid (VS) in digestate = $(1-w_1) \times Y \times Z_1$

Total Solid in leachate (%) = w_L
Solid in leachate (g/L) = S_L
Liquid in leachate = $(1-w_L) \times L$
Volatile solid in leachate (g/L) = VS_L

Water balance

Based on mass conservation, the amount of VS and leachate withdrawal must be equaled VS and water loaded into the reactor. Therefore, the total water entering the reactor must be equal to the total water leaving the system. If total liquid in leachate from the digester is $(1- w_L) \times L$ and total moisture in the digestate is $(w_1 \times Y)$, and assuming that the water loss from the evaporation of biogas is neglected, Therefore, water mass balance can be expressed as:

Total liquid in = Total liquid out

$$(w \times X) = (w_1 \times Y) + (1-w_L) \times L$$

So the total leachate withdrawal = $\dfrac{(w \times X) - (w_1 \times Y)}{1 - w_L}$ Eq. 3.2

Volatile solid mass balance

The leachate to be withdrawn contain volatile solid calculated by the formula $(L \times VS_L)$. Moreover, some solid is lost in the biogas production (kg) as given in Eq. 3.1. If the amount of dry digestate to be withdrawn is y, the mass balance equation is written as:

Volatile Solid (VS) intake = Volatile Solid (VS) out

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

Eq.3.3

Total digestate to be withdrawn (kg) $Y = \dfrac{(1-w) \times X \times Z - (L \times VS_L) - G_m}{(1-w_1) \times Z_1}$ Eq.3.4

d. Digestion process operation

For the start-up operation, the prepared feedstock was loaded into the reactor after mixing well with the inoculums. The amount of first feeding was 80% of the reactor volume. As the reactor volume is approximately 770 L and the density of compacted waste was approximately 600 kg/m^3. 296 kg of fresh waste was loaded with 20% of inoculums. Then, mixing was provided through leachate percolation to enhance the digestion process and biogas production. Mature leachate obtained from previous research was used for percolation at the rate of 500 mL/min for 3 hours daily from the first day of the process. It should be noted that mesophilic condition (37°C) was employed for starting up the reactor to acclimatize the inoculums together with substrates, and then it was shifted to thermophilic condition (55°C) by gradually increasing the temperature at rate of 2°C per day to avoid thermal shock to microorganism. The subsequent experiments were carried out in thermophilic condition. pH adjustment was definitely done for the first 10 days of operation by using commercial grade NaOH to shorten the digestion time and enhance the anaerobic digestion. Daily monitoring of some important parameters such as pH, alkalinity, VFA, biogas production as well as biogas composition was conducted.

Daily monitoring of biogas production was conducted. No feed was provided to the reactor, until the digestion process was stabilized. Once, the decrease of biogas production was observed, continuous feeding and withdrawing mode of operation was started.

When fresh material continuously entered the digester and equal amount of digested waste was withdrawn. This was done before the feedstock was added through material balance analysis as described earlier in the previous section. Experiments on progress, increased loading rate was also done. The scheme of loading rate is depicted in Table 3.1.

Table 3.1 Loading profile for continuous operation

Loading description	Loading rate in wet weight (kg/day)	Loading rate (kg VS/m^3.day)	Mass retention time (Days)
Loading 1	12.5	2	25
Loading 2	16	2.5	20

Mass retention time is defined as the active reactor mass (kg VS) divided by the total wet mass fed each day (kg VS) (Kayhanian & Rich, 1995), was used to determine the digestion time for each loading rate. By using the data from previous researcher (Adhikari, 2006), each loading rate can be estimated. The summary of experimental runs in two phases which are; phase 1: Reactor start up and phase 2: Continuous feeding was shown in Table 3.2. The mass balance calculation was done by using simple calculation which already described in the above section.

Table 3.2 Pilot scale experimental reactor runs

<table>
<tr><th colspan="3">Phase 1: Reactor starts up</th></tr>
<tr><td colspan="3">- Particle size = 10 mm
- Waste weight = 296 kg
- Inoculum addition = 20% of substrate, consist of cow dung, anaerobic sludge digested waste and matured leachate with the proportion 2:1:1:1)
- Leachate percolation = 500 mL/min for 3hours daily
- Temperature = mesophilic range and 2°C increase per day to thermophilic condition (55°C)
Note: pH adjustment was done during the first 10 days of operation</td></tr>
<tr><th colspan="3">Phase 2: Continuous feeding</th></tr>
<tr><td>Loading</td><td>Constant</td><td>Variable</td></tr>
<tr><td>Loading 1
↓</td><td>- Particle size 10 mm
- Feeding and withdrawing mode of operation through material balance analysis
- Leachate percolation 500 mL/min for 3 hours daily
- Temperature : thermophilic condition</td><td>- Mass retention time: 25 days
- Loading 1: 2 kg VS/m^3.d</td></tr>
<tr><td>Loading 2</td><td>- Particle size 10 mm
- Feeding and withdrawing mode of operation through material balance analysis
- Leachate percolation 500 mL/min for 3 hours daily
- Temperature : thermophilic condition</td><td>- Mass retention time: 20 days
Loading 2: 2.50 kg VS/m^3.d</td></tr>
</table>

3.3 Lab scale analysis: Biochemical Methane Potential (BMP) test

The analysis in the laboratory scale was conducted to determine the methane potential of substrates by using Biochemical Methane Potential (BMP) test. The following section describes the detail procedure and the important of BMP test.

3.3.1 BMP test procedure

Biochemical methane potential (BMP) analysis is an efficient and cost effective method for analyzing the rate and extent of biomass conversion to methane under anaerobic conditions.

The experiment was conducted in duplicate because the method is used a biological process and homogenization of feedstock is very important to ensure the representative sample (Hansen, et al., 2004).

In this study, BMP test was conducted using OFMSW as substrate and anaerobic sludge as seeding. 2.5 L reactors were used which had the rubber stopper to take the sample easily. There were 4 reactors. Blank reactors contained a combination of 100 mL of water and 400 mL of inoculums. Total volume in each reactor was 500 mL. The detail procedure of BMP analysis is described in Figure 3.4.

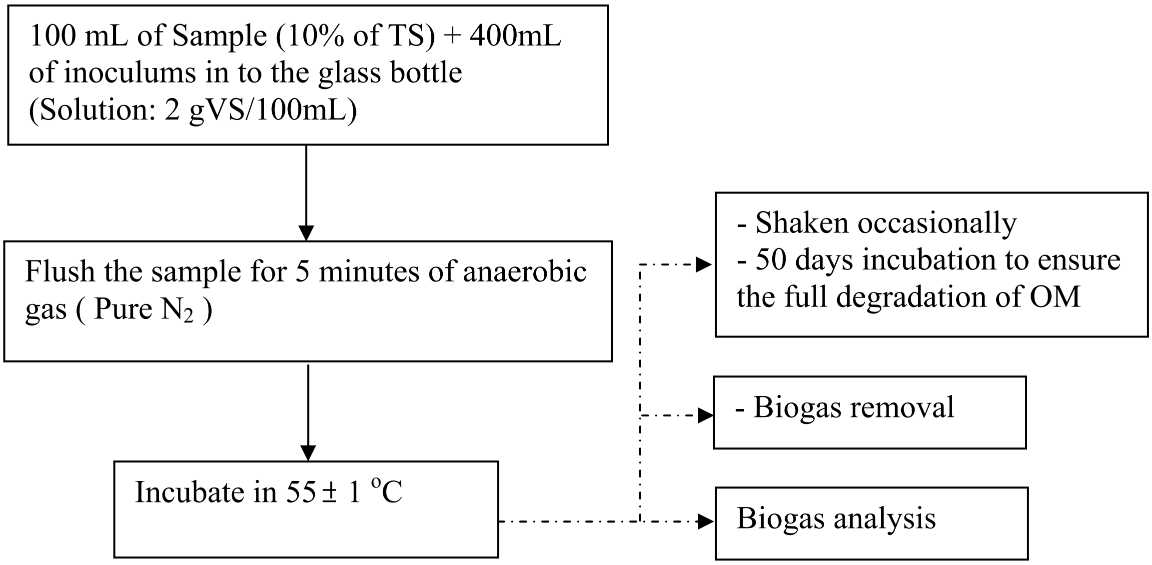

Figure 3.4 Biochemical Methane Potential assay in lab scale (Hansen et al., 2004)

3.3.2 Equipment and supplied needed for the BMP assay

Pulverizer: For particle size reduction into fine solids (approximately 2 mm)
Two- liter glass bottles with thick rubber septum to be used as reactors. The exact volume of each bottle is determined by filling the bottles with a measured volume of water.
An incubator of 55°C for the incubation of sample
Active inoculums.
A 1 mL glass syringe with pressure locks to allow sampling of a fixed volume at actual pressure from the reactors.
Gas chromatograph.
Gas mixture of 80 % of N_2 and 20 % of CO_2 (alternatively pure N_2 gas can be used)

Blank is always necessary and was carried out with only water and inoculums to measure the methane potential originated from the inoculums.

3.3.3 Importance of Lab-scale BMP test

As mentioned earlier, the BMP test was conducted in laboratory scale test set-up to investigate the possible methane generation potential on organic fraction of municipal solid waste. This test was able to provide an indication of the methane potential variation in comparison with the pilot scale anaerobic reactor to determine the process efficiency. Furthermore, it was very simple and has the potential of being used for the measurement of the potential methane generation and for the enhancement and the limitation of methane potential. Moreover, the data is reliable with less operational costs required.

3.4 Sampling and analytical methods

Sampling and analysis in this study was done for heavy metals (fresh and digestate), solid waste (fresh, digestate and inoculums), nutrient analysis (Nitrogen, Phosphorus and Potassium) for fresh as well as digested waste. Leachate characteristic and biogas production and composition were monitored on a daily basis. The procedure of each experiment is described in details in the following section.

3.4.1 Heavy metals analysis

Heavy metals selected in this study for determination include; Cadmium (Cd), Lead (Pb), Zinc (Zn), Copper (Cu), Chromium (Cr), Nickel (Ni), Manganese (Mn), Mercury (Hg), which may be present in many kinds of wastes like fertilizers, household wastes and industrial wastes. Table 3.3 describes the sample preparation and analytical methods involved. It is noted that the applicable range and accuracy is 1-10mg/L, avoid storing in soft glass container for sample in microgram per litter range as well as precipitation and adsorption container.

Table 3.3 General information on heavy metals analysis parameters

Parameters	Method/instrument	Sample handling
Cadmium (Cd)	ICP (Inductive Couple Plasma)	Acidify to a pH<2 with nitric acid, then keep at 4 ° C for 6 months
Lead (Pb)	"	“
Zinc (Zn)	“	“
Copper (Cu)	“	“
Chromium (Cr)	“	“
Nickel (Ni)	“	“
Manganese (Mn)	“	“
Mercury (Hg)	“	Acidify to a pH<2 with nitric acid, then keep at 4 ° C for 5 weeks

3.4.2 Analysis of solid waste characteristics

Homogenous samples were taken to determine the dry matter content of the original sample. To calculate the mass reduction of solid waste after anaerobic digestion, the waste characteristics needed to be analyzed. Figure 3.5 represents the detailed procedure of the solid waste analysis. The general information on solid waste analysis is depicted in Table 3.4. The solid waste analyses were based on ASTM (1993).

Moisture content determination

Moisture is defined as the amount of water lost from dry matter upon drying to a constant weight, expressed as the weight per unit of dry substance or as the volume of water per unit bulk volume of the substance. Samples were taken from either raw or digestate waste. Aluminum trays were filled with around 1 kg of sample and then place in oven 103-105° C for 24 hours, the weight losses were obtained. The same procedure was repeated until the difference of weight loss was less than 3%. Then the moisture content and total solid was calculated based on Eq. 3.6 and 3.7. Finally, the average value was obtained.

$$\%MC = \frac{1000 - w_0}{1000} x100\% \qquad \text{Eq.3.5}$$

Where w_0 : Weight of sample after drying

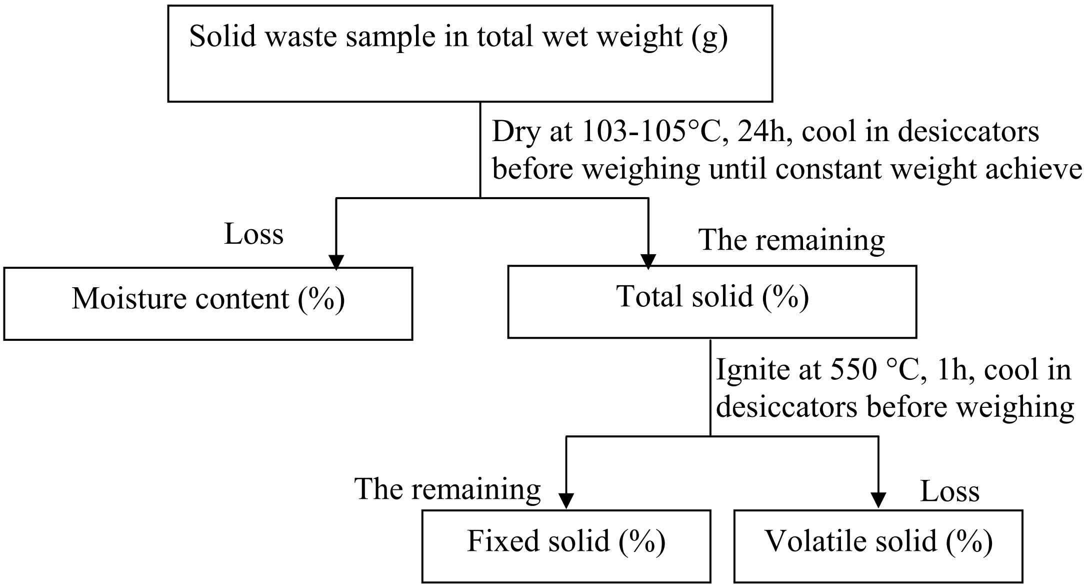

Figure 3.5 Solid waste analysis procedures

Thus, the total solid is calculated by subtracting the percentage of MC from 100 as shown below:

$$\%TS = 100\% - \%MC \qquad \text{Eq.3.6}$$

Volatile solid determination

The same sample was used for moisture content analysis was again used for volatile solid analysis. Several samples each of size 2 g were put in evaporating dishes which had been ignited at 550 °C for at least one hour in a muffle furnace. The empty dishes were immediately weight after cooling to room temperature. Initially, the solid samples were evaporated to dryness in an oven at 103-105 °C for at least one hour. Then the samples were cooled to room temperature in desiccator and weight on an analytical balance. The cycle of drying, cooling, desccating and weighing was repeated until a constant weight was obtained. Then, the samples were ignited in a muffle furnace at 550°C for one hour. After that, they were kept in a desiccator and weights were obtained. The cycle of igniting, cooling, desiccating and weighing was repeated until a constant weight was obtained. The volatile solid of each dish was calculated using Eq. 3.8. Finally, the average value was obtained.

$$\%VS = \frac{w_0 - w_f}{w_0 - w_e} x100\% \qquad \text{Eq.3.7}$$

Where w_0 : Weight of the sample and evaporated dish after drying at 103-105°C

w_f : Weight of the sample and evaporated dish after igniting at 550°C

w_e : Weight of the empty evaporated dish

Equation 3.9 (Gottas, 1977 cited in Dayanthi, 2003) was applied to obtain the total carbon in both fresh and digestate waste sample.

$$\% \text{ Total carbon} = \frac{\%VS}{1.8} \qquad \text{Eq.3.8}$$

Total solid and volatile solid loss determination

The material balance analysis is shown in Figure 3.6. The loading substrate has total a weight of TW_0 and a dry weight of M_0. After entering the reactor and being digested, the reduction of solid and volatile solids were occurred. Therefore, the residual had a total weight of TW_1 and a dry weight of M_1 which were less than that of TW_0 and M_0, respectively.

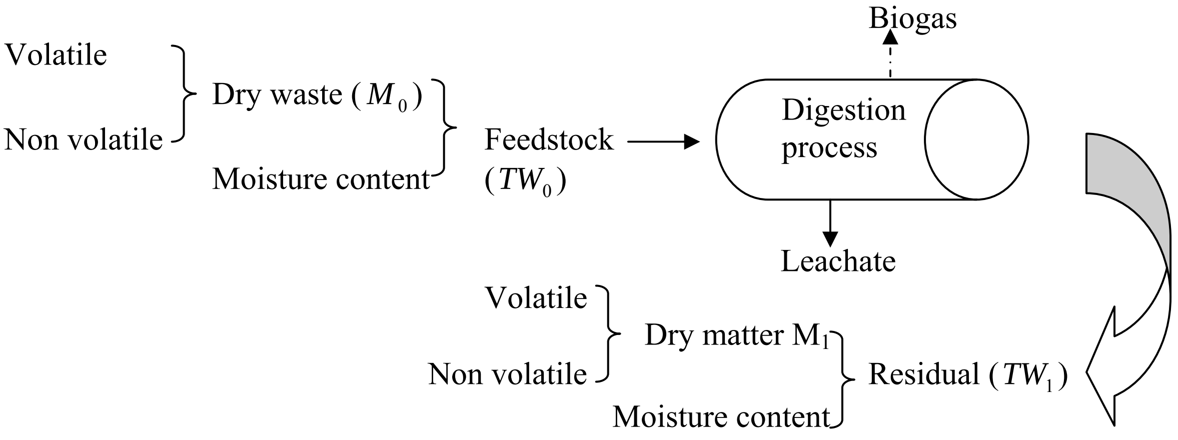

Figure 3.6: Material balance analysis in anaerobic digestion process

The equation below was used to estimate the percentage of total solid loss (%TS loss) and percentage of volatile solid loss (%VS).

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

Where M_0 : Dry weight of feedstock going in the reactor (g)

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

TW_0 : Wet weight of solid waste going in the reactor (g)
TS_0 : % total solid of feedstock (%TW)
M_1 : Dry weight residual going out reactor (g)

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

TW_1 : Wet weight of residual going out of the reactor (g)
TS_1 : % total solid residual (%TW)

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

Where N_0: Weight of volatile fraction going in the reactor (g)

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

VS_0 : % volatile solid of feedstock (%TS)
N_1 : Weight of volatile fraction of residual going in the reactor (g)

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

VS_0 : % volatile solid of residual (%TS)

Table 3.4 General information on solid waste analysis parameters

Parameters	Method/instrument
Moisture content (%)	Gravimetric analysis
Total solid (%)	Gravimetric analysis
Volatile solid (%)	Muffle furnace

3.4.3 Nutrient analysis

Both fresh and digested wastes were analyzed for nutrients (N, P, K) content. In general, they are the major component found in MSW. N, P, K are the macro nutrient which are essential for the growth of microorganisms. Table 3.4 depicted the general information on nutrients analysis.

Table 3.5 General information on nutrients analysis

Parameters	Method/instruments	Detection limits (mg/L)
N (%)	Macro- Kjeldahl analysis	-
P (%)	Spectrophotometer	0.02
K (%)	AAS	0.01

In addition, some important parameters were selected to analyze digested waste such as. Total Carbon (TC), Total Nitrogen (TN), Total Phosphorus (P), Total potassium (K), calorific value and selected heavy metals were analyzed to check whether it meets the composting standards set by some selected developing countries or not. Calorific values were analyzed using bomb calorimeter (CAL2k- ECO).

3.4.4 Analysis of leachate characteristics

Leachate analysis was carried out from the starting up of the process until the final phase on daily basis. Moreover, pH needs to be measured immediately during the field sampling. Next, the following parameters were measured in the laboratory:

Total Dissolved Organic Matter (DOC)
Soluble Chemical oxygen demand (SCOD) and TCOD
Volatile fatty acid, comprised of acetic acid, propionic acid, isobutyric acid, n-butyric acid and valeric acid
Nitrogenous species: NH_4 - N, TKN (Total Kjeldahl Nitrogen)
Alkalinity
Sulfate (SO_4^{2-}) and Sulfide (S^{2-})
Heavy metals (Cadmium (Cd), Lead (Pb), Zinc (Zn), Copper (Cu), Chromium (Cr), Nickel (Ni), Manganese (Mn), Mercury (Hg)

Leachate analysis was conducted by following the Standard Method for Examination of Water and Wastewater (APHA et al., 1998). Table 3.4 lists the parameters to be analyzed, interference, as well as precautionary principles during the sampling and analysis.

3.4.5 Biogas analysis

Biogas monitoring and analysis were conducted on the daily basic by using a wet gas meter (Ritter TG 05, Germany). The sample was taken by inserting gas syringe into U tubes, then a Gas Chromatograph (SHMADU-GC14A, Japan) equipped with a thermal conductivity detector, was used to measure the composition of biogas. It is noted that the biogas comprises of H_2, CO_2, CH_4, O_2 and N_2. However, biogas is mainly composed of CO_2 and CH_4. The details of analytical conditions for GC are depicted in Table 3.6.

The actual temperature and atmospheric pressure are recorded; these values are used to determine the biogas content at standard temperature and pressure according to:

$$V_s = V_m \frac{T_s . P_m}{T_m . P_s} \qquad \text{Eq.3.16}$$

Where T_m : ambient temperature (°K)

P_m : Ambient pressure
V_m : Volume of gas at ambient condition
T_s : Standard temperature ((0°C = 273 °K)
P_s : Standard pressure (1013.25mb)

Thus, the result was obtained in methane produced per gram VS at standard temperature conditions (STP: °C, 1atm).

Normally, the digester gas is saturated with water vapor, and then the dry volume of gas can be calculated by:

$$\text{Dry volume} = \frac{P_b(\text{Volume of gas sample})}{P_b - P_v} \qquad \text{Eq.3.17}$$

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

3.5 Energy production and consumption

The energy production and consumption in this study were done to evaluate the potential energy produced in the process to evaluate the economy of the process. Practically, in continuous process there were only two kinds of energy consumption had been observed namely, shredding and heating. However, only one source of energy recovery was from biogas production which can be use as a source of electricity or heating purpose.

Table 3.6 General information on leachate analysis parameters

Parameters	Method/instrument	Sample handling	Applicable range and accuracy	Interferences	Precaution (sampling and analysis)
pH	pH meter electrode	Immediate analysis	(1-14) ± 0.1	Sodium if pH>10 and temperature	Meter calibration should be done periodically
SCOD/TCOD (mg/L)	Closed dichromate-reflux titration method	Refrigerator (4°C), 7days	>50mg/L, not applicable if Cl^- >2000mg/L	Halides ions: Chloride, Nitrite	Add $HgSO_4$ to eliminate chloride and sulfamic acid to remove nitrite
DOC (mg/L)	TOC analyzer/High temperature combustion	Refrigerator (4°C), 7days	>20ppm, 5-10%	Inorganic carbon	Adding acid to get pH 2 and purging of acidified solution
Alkalinity (mg/L as $CaCO_3$)	Titration method	Refrigerator (4°C), 24 hours	Standard deviation; 5mg/L	Soap, oily matter, suspended solids	Allow additional time between titration; no filter
VFA (mg/L)	Gas chromatograph (SHIMADU-GC14 A with TCD detector)	Immediate analysis	95% accuracy	Presence of synthetic materials like detergents	
NH_4-N (mg/L)	Standard method 4500B: Distillation method				
TKN (mg/L)	Standard method 4500B: Macro kjeldahl method	Refrigerator (4°C), 24 hours	<5mg//L	Nitrate>10mg/L, inorganic salt and solids	Fresh sample is preferable, blank is always necessary
SO_4^{2-} (mg/L)	Turbidimetric method	Refrigerator (4°C), 28 days	1-40mg/L	High Color or suspended matter, Silica excess 500 mg/L	Make determination in room temperature with variation 10°C.
S^{2-} (mg/L)	Iodometric method	Refrigerator (4°C), 28 days	0.1 mg/L in 200mL sample		Minimum aeration is required while taking sample
Cd, Pb), Zn, Cu, Cr, Ni, Mn	ICP-AES	Acidify to a pH<2 with HNO_3 , keep at 4 ° C for 6 months			
Hg	ICP-AES	Acidify to a pH<2 with HNO_3 , keep at 4 ° C for 5 weeks			

Table 3.7 Analytical conditions for Gas Chromatography

Description	Biogas	Volatile fatty acids (VFA)
Detector	Thermal conductivity	Flame Ionization Detector (FID)
Carrier gas	He	N_2
Flow rate	40 mL/min	40 mL/min
Injection/Detector Temperature (°C)	50/100	210/210
Column Temperature (°C)	50	100-300°C, 10°C/min, 130°C (5min) to 175, 10°C/min, 175°C (7.5min)
Column	Pack (WG-100, SUS col., Inner diameter 1.8 mm	Capillary, DBFFAP (30 mm x inner diameter 0.32 mm x thickness 0.25µm
Sample volume (mL)	0.2	0.001

Chapter 4

Results and Discussions

This chapter focuses on the findings obtained from laboratory scale BMP analysis and pilot scale inclined type anaerobic continuous reactor. As mentioned in chapter 3, these experiments were conducted under thermophlilic condition using OFMSW as the substrate. The size of the substrate used in this study was approximately 10 mm. The later part of this chapter is the result from BMP test in laboratory scale. Its result is avail to compare the process efficiency.

4.1 Continuous Anaerobic Digestion Reactor

4.1.1 Feed stock preparation and analysis

Solid waste sample was collected from Klong 5 dumpsite, Taklong Municipality, Pathumthani Province, Thailand. The raw materials consisted of food wastes emanating from fruit and vegetable markets as well as household waste of the municipality. The waste was collected and then mixed and shredded to get particle size 10 mm (Appendix A) in such a way similar to that used to prepare the substrate for vertical reactor (Adhikari, 2006). Feedstock adequate at least for three to four weeks was prepared and stored at 4 C. The stored waste was kept in room temperature for about at least 2-3 hours before feeding to the reactor to avoid the temperature shock to microorganism. The chemicals and physical analysis of samples analysis were carried out for every collection in triplicate and the results are illustrated in Table 4.1 in average value.

Table 4.1 Solid waste and seeding characteristics

Sample	Moisture content (MC) (%WW)	Total solid (TS (%WW)	Volatile solid (VS) (%TS)	Fixed solid (FS) (%TS)
Solid waste	88-91	9-12	82.32-83.67	17.68-16.33
Anaerobic sludge	92.72	7.27	46.05	53.94
Mature leachate	98.95	1.04	24.47	75.52
Digestate waste	60.57	39.43	39.27	60.73
Cow dung	58	42	74	26

Physically, the dominant factor over the characteristic of raw waste was the high moisture content. High moisture content was cause by the high fraction of fruit peels and vegetables straps. It is the reason for waste to have very high moisture content and high organic fraction (Volatile Solid).

However, the presented parameters could not exactly reflex the potential of the waste in the anaerobic digestion process. Methane potential would be more valuable to examine the response of the waste to anaerobic digestion which is described in the next section.

The biodegradable fraction of MSW is rather a heterogeneous substrate and the biogas yield in the AD treatment of OFMSW depends on not only on the process configuration, but also on the waste characteristics. Nutrients are the important parameters in estimating nutrient deficiency (Hartmann & Ahring, 2006). Therefore, in addition to the chemicals characteristics of feed stock and inoculum, nutrient analysis of substrate has been done before loading as depicted in Table 4.2. The C/N ratio is determined by its composition. C/N of feedstock in this study was found 15 similar to that of Castillo et al., (2006) which studied on urban solid waste in Columbia with 15.85 C/N ratio. As stated by Kayhanian & Rich (1995), a feedstock for anaerobic digestion process with a greater C/N than 30 is considered to be deficient in nitrogen for a biological treatment. Thus, it can be concluded that there would be any nutrient deficiency since the C/N ration of substrate in this study was found lower than 30. Comparably, Phosphorus and Potassium was found to be in the same range like what Castillo, et al., (2006) reported.

Table 4.2 Nutrient analysis in feedstock

Parameters	OFMSW
N (% D.M)	3.04
P (% D.M)	0.22
K (% D.M)	0.22
C (%)	45.73
C/N	15.04

To study the fate of selected heavy metals in digestion process, solid waste analysis in term of heavy metals contamination was analyzed. However, the result presented in the Table 4.3 indicated that the low percentage of those metals as it might be the fact that this feedstock had been separated and selected only the biodegradable fraction, then the low heavy metal contamination was achieved as the heavy fraction as well as non biodegradable were taken out before sample analysis. These results were found in line with the data reported by Chynoweth & Pullammanappallil (2005) who conducted the research on anaerobic digestion of MSW.

Table 4.3 Heavy metals analysis in feedstock

Heavy metals	Concentration (mg/ kg D.M)
Cadmium (Cd)	0.25
Lead (Pb)	ND
Zinc (Zn)	72.24
Copper (Cu)	15.29
Chromium (Cr)	7.36
Nickel (Ni)	4.10
Manganese	88.10
Mercury (Hg)	0.036

As mentioned earlier, the experiment in this study was conducted in two phases namely reactor start-up and variation of loading. The detailed of each phase is described in the following section.

4.1.2 Phase 1: Reactor start-up

The experiments have begun with reactor starts up (Phase 1) for digestion process. The reactor was fed with 296 kg substrates, which is equal to 80% of reactor volume since total volume of reactor is 770 L with compaction density of 600 kg/m^3. It was noted that the substrate was well mixed with 20% of inoculum which comprised of 29.6 kg of cow dung, 14.8 kg of digestate waste, 25 L of anaerobic sludge and 25 L of mature leachate before loading to the reactor to initiate the digestion process. It is not that necessary to acclimatize inoculum since this experiment was conducted in mesophilic for the first starting up and then it was gradually increased by 2°C/day until reaching the optimum thermophilic range (55°C) (Adhikari, 2006). This can be used as the strategy to avoid the temperature shock load to microorganisms as well as acclimatize the inoculum in the same vessel. Moreover, mixing mechanism was provided through leachate percolation with the rate 500 mL/min for three hours daily to enhance biodegradability of the substrates.

a. Biogas generation and methane efficiency

Biogas production and methane production were selected as the primary indicator to evaluate the performance efficiency of the reactor. It was noted that the degradation of substrate started almost immediately after loading started. During the first 4 weeks, there was no feeding was applied since the biogas production was increasing gradually. It was observed that from day 1 to day 8, there was the fluctuated of biogas production and from day 9 to day 19, then it was increased sharply (Figure 4.1). Likewise, methane composition in biogas was increasing from the day 1 and reached maximum value of 66% at day 19 (Figure 4.2). The highest volume of biogas production (520 L/ day) was also achieved at the same day. Figure 4.1 depicts the wide variation in biogas production. The trend of accumulative gas production is figured out to provide the better explanation of the relationship between daily gas productions versus time. It is clearly seen that the volume of gas is increase with the longer operational days indicating the good performance of the reactor (Table D-3).

After day 20, the volume of biogas produced showed a decreasing trend, indicating the limited substrate in the reactor. However, methane composition still varied in the very close range. Then, the feeding and decanting mode of operation were started from day 30 onwards.

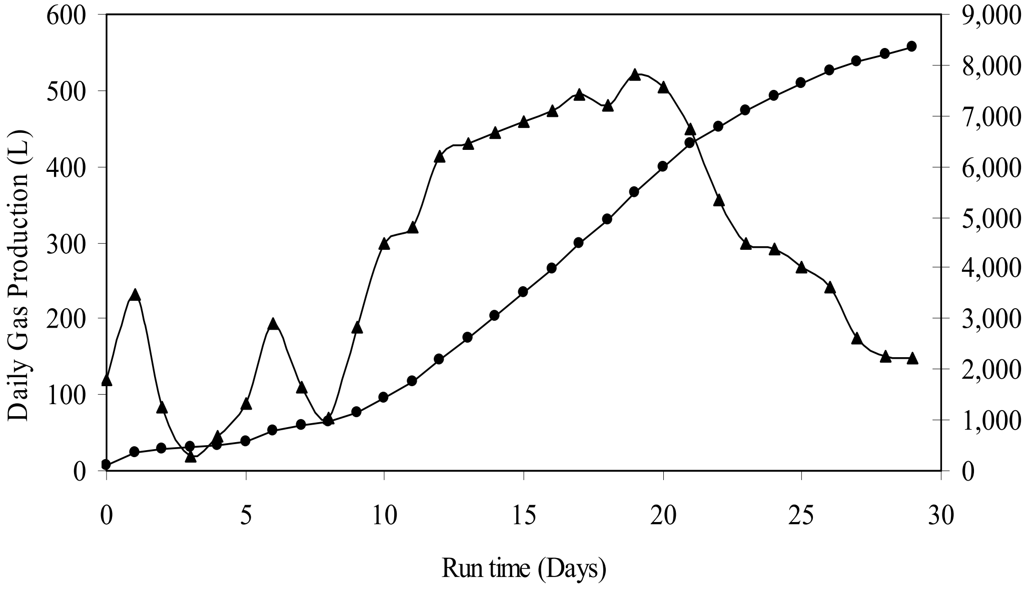

Figure 4.1 Daily and accumulative gas production during star up period

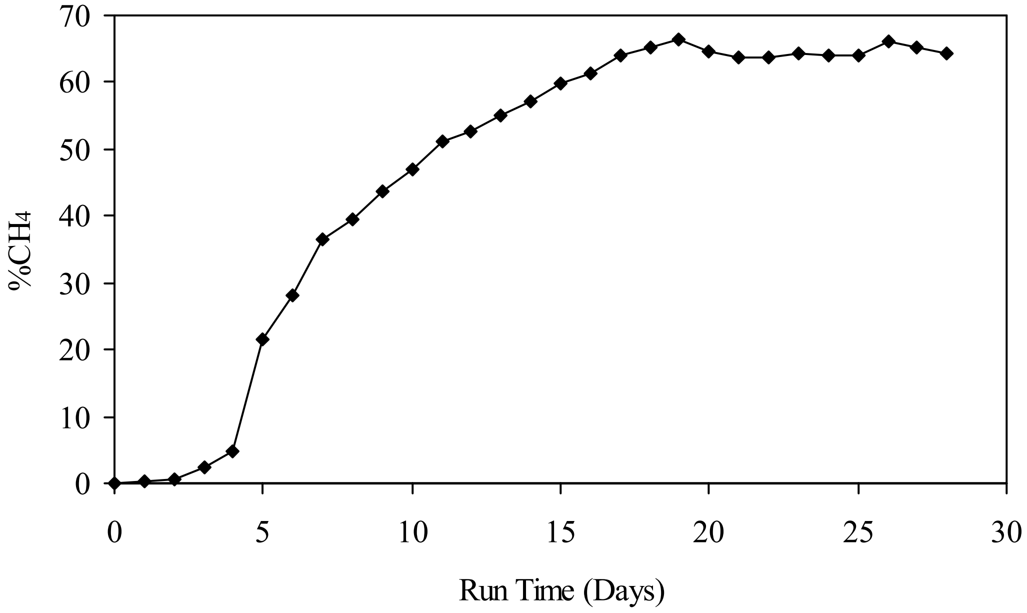

Figure 4.2 Trend of methane composition in biogas during start up operation

b. Leachate characteristics

pH and alkalinity variation during the started up period are shown in Figure 4.3. The pH value of 7 and the concentration of methane 50% were taken as a sign of active methane phase. However, during the first 2 weeks of operation, pH value was below 7. This could inhibit the methanogensis reaction. pH of the system was adjusted to 7 using commercial grade NaOH. It was done from the starting day until day 10; to which pH reached 6.97 as it was already the optimum range for methanogenesis. From day 10 to day 29, the pH and alkalinity value were relatively stabilized with slightly fluctuating in a very small range showing the good performance of the reactor as depict in Figure 4.3.

Figure 4.4 shows the variation profile of pH and VFA concentration which were in a appropriated trend from initial day to last day of star-up. The highest concentration of VFA found was on day 3 with the lowest pH of 5.8. It can be concluded that there was a high acidification at day 3 and the system lacks of sufficient buffering as indicated by lower alkalinity of the system. Because of that reason, pH adjustment was done to increase the pH and activated the microorganisms as described in previous section, due to the enzymatic activity of methane forming bacteria does not occur below pH 6.3 and methanogenesis was favored at a pH between 6.8 and 7.2 (Chen et al. (1996). pH adjustment thus aided the system in starting up the process of methanogenesis. After that, the pH of leachate stabilized in the small range 7-7.8. Interestingly, VFA concentration which reached optimum at the first few days then dropped gradually and thereafter remains constant in the range 1,000mg/L as the indication of the balance condition of this running system (Table D-1).

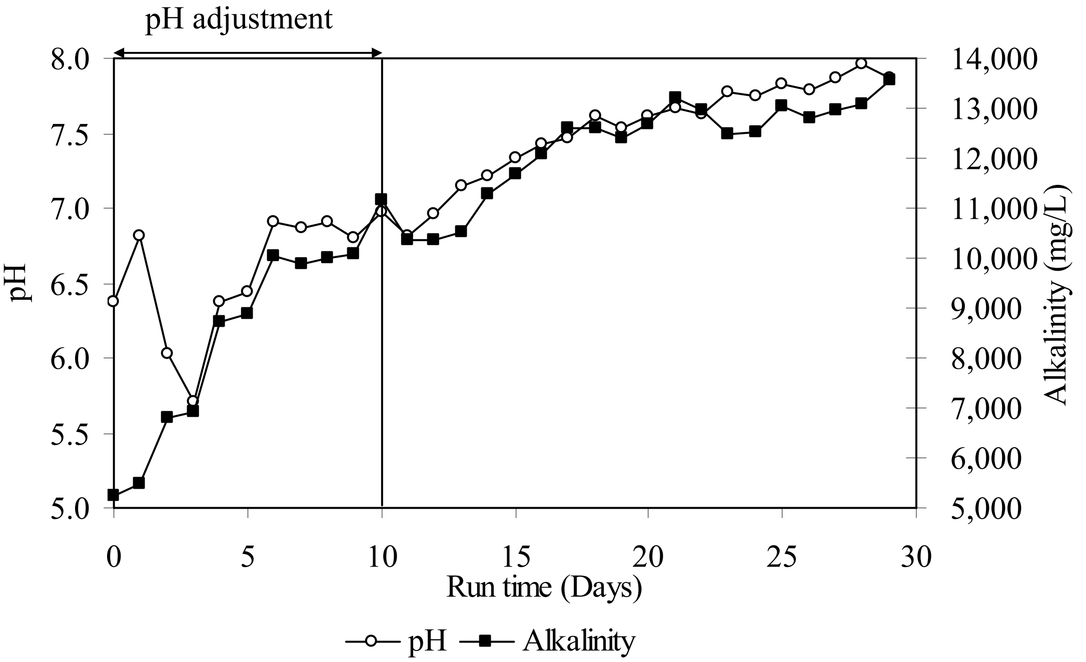

Figure 4.3 Variation between pH and alkalinity

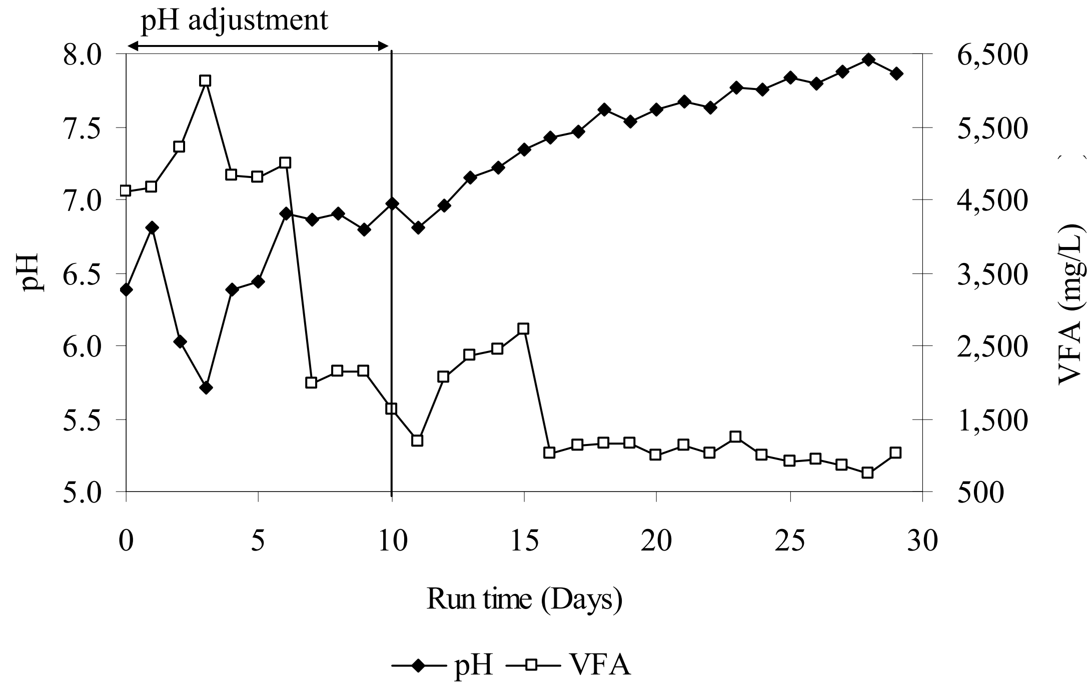

Figure 4.4 Profile of pH and VFA concentration

The organic matter contained in the substrate can be measured by mean of any selected parameters such as DOC, SCOD and COD. The Figure 4.5 presents the variation of these three parameters during the start-up of operation. The significant increases in COD in leachate can be observed as the sign of active hydrolysis phase. Comparing COD and SCOD in leachate, it seems that soluble organic matter is the major fraction of total organic in solid waste. COD and DOC started to increase and reached the optimum value in day

11, then it is started to decrease there after. Based on Adhikari (2006), was reported that COD of leaching reached maximum on day 10 and when the concentration of COD increased, DOC was also increased. Therefore, DOC can be used as the interesting parameter in evaluation of the reactor performance.

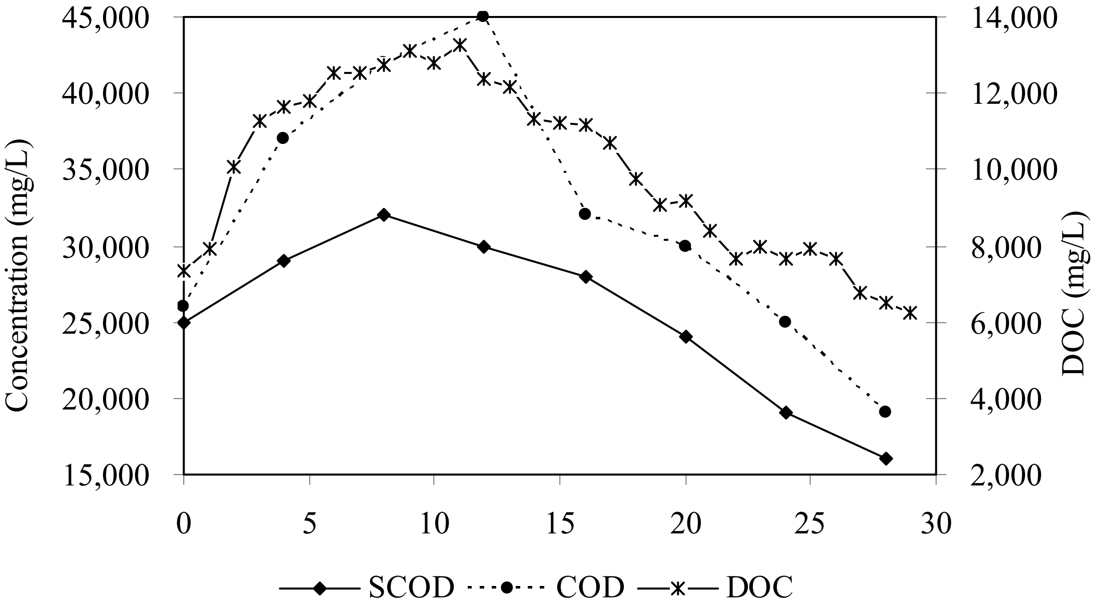

Figure 4.5 Variation of SCOD, COD and DOC in start up operation

Protein is hydrolyzed into amino acid and then further degrades to ammonia nitrogen and TKN. Therefore, NH_4-N is one of the hydrolysis products formed during the degradation of nitrogenous material in solid waste/substrate. Figure 4.6 presents the daily ammonia-N and TKN which can be translated in terms of degradation of protein presenting in feedstock. The presence of NH_4-N and TKN can always be of concern in anaerobic digestion as it can cause inhibitory to the system. In the pH range of 6.5-8.5, methanogenic activity decreased with increased in ammonia-N concentration, and dropped to zero at the concentration of 6000 mg/L (Mata-Alvarez, 2000). In this experiment, the concentration of NH_4-N increased from 1000 mg/L to 1568 mg/L in day 29. However, it does not appear any inhibitory since the inhibition by NH_4-N is 1200mg/L as reported by Mata-Alvarez (2003) because pH in the system is in the higher range from 7.4 up. Likewise, TKN also exhibited similar trend increasing from 1500 mg/L to 2000 mg/L which mainly comprised of ammonia-N.

There are several physical and chemicals factors in the environment that affect biodegradation of organic compounds. One of the major factors governing biodegradation is the nature and availability of electron acceptors. In anaerobic condition, the biodegradation will often depends on the availability of electron acceptors, such as nitrate, iron, sulfate or carbon dioxide. As reported by Angelidaki (2002), sulfate reducers are able to outgrow the methanogens. This is due to the high energy gained by sulfate reduction compared to methanogenesis. Thus, the too high concentration of sulfate will result in the reduction of methane potential of the substrate in anaerobic digestion process. However, the presences of sulfate can also beneficial effect on anaerobic treatment of wastewater. Sulfide produced from microbial reduction of sulfate can precipitate toxic heavy metals (Isa et al., 1986).

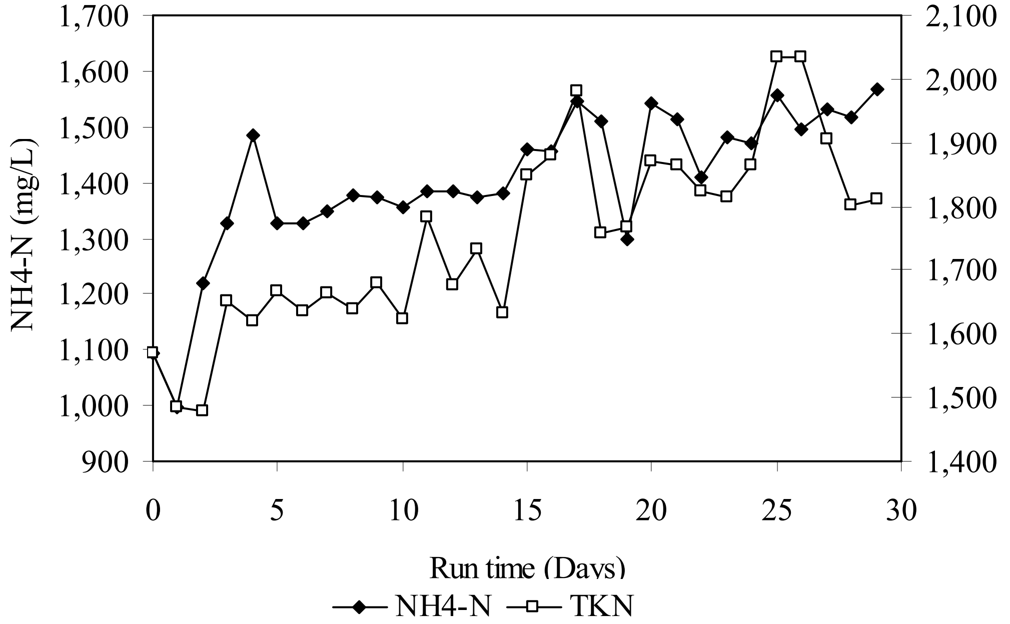

Figure 4.6 Profile of NH_4-N and TKN concentration

In this present study the maximum concentration of sulfate was achieved at day 12, meanwhile the lowest sulfide concentration was also found in the same day as shown in Figure 4.7. It has been investigated that since the reduction of sulfate occurred, than the concentration of sulfide is increased. This is due to the fact the sulfide is produced from microbial reduction of sulfate. The optimum value of sulfate in this study was 6500 mg/L; however, there was not any inhibited was observed. This is in the line with Isa (1986) who confirmed that sulfate level up to 5000 mg/L have no significant impact on methane production. It was noticed that sulfide concentration was also observed at maximum value at the same days sulfate. However, it was confirmed by SD-FAO (2005) who conducted the research on anaerobic digestion of MSW that there is no any inhibitory occurred if sulfate value is still below 5000 mg/L. Similarly Chynoweth & Pullammanappallil (2005) reported that there is no inhibition was observed if sulfide concentration is less than 600 mg/L. As Sulfate concentration showed a reducing trend and sulfide was increasing, these parameters were not monitored for the rest of the experiments.

The presence of heavy metals ions in anaerobic environments can acts as either stimulant or inhibitor. However, as the reference values concentration over 1 mg/L of heavy metals can be toxic to anaerobic digestion process (E.P.A, 1974, cited in Mata-avarez, 2003). For concentration of selected heavy metals of this study, the analysis was done only in day 0 (First loading day) and day 29 (Last day for start-up period) for phase one period. As the result, the concentration of all selected heavy metals was far below 1 mg/L as presented in Table 4.4 since the substrate used was only the biodegradable part and non biodegradable or plastic bags were separated before shredding. Thus, it can be used as the evidence that there was even no any adverse effected or inhibition from heavy metals which may cause the toxicity to microorganisms in the process if the higher concentration was found.

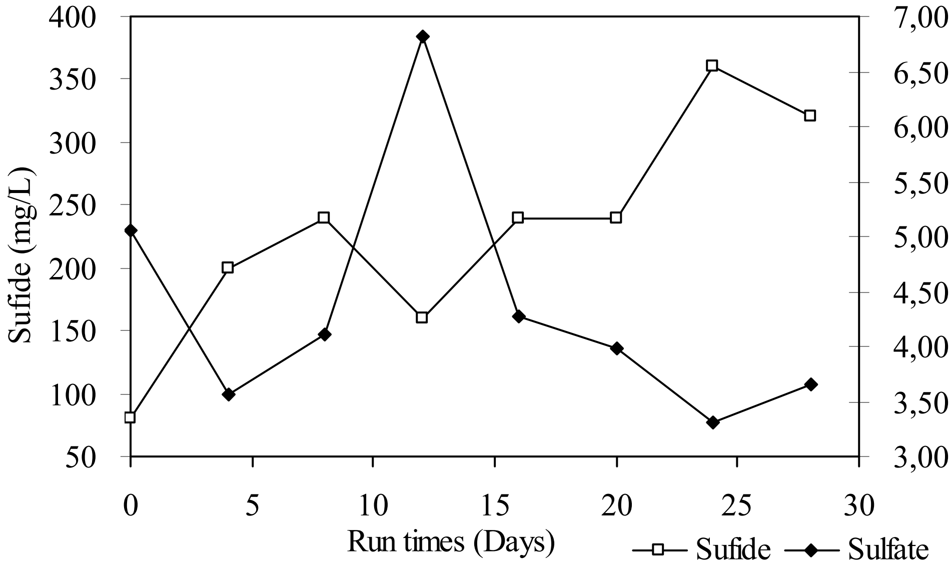

Figure 4.7 Profile of SO_4^{2-} and S^{2-} concentration

Table 4.4 Heavy metals concentration in leachate

Heavy metals	Concentration (µg/L)	
	Runt time (Day 0)	Run time (Day 29)
Cadmium (Cd)	2.44	3.20
Lead (Pb)	0	0
Zinc (Zn)	648.69	399.20
Copper (Cu)	166.83	372.33
Chromium (Cr)	56.61	51.35
Nickel (Ni)	378.78	222.19
Manganese (Mn)	838	861.18
Mercury (Hg)	0.79	0.69

As explained in the previous section, this research was divided into two parts: Phase 1: reactor star-up and Phase 2: continuous feeding for two different loading rates and digestion times. Therefore, the result of this second phase of operation and its efficiency was revealed in the following section.

4.1.3 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 two different Mass Retention Times (MRTs) of 25 and 20 days. The loading rate was gradually increased as the mass retention time was decreased. The experimental runs at Phase 2 were carried out in a sequentially scheduled routine beginning with the 25 days digestion time period. Once the reactor is operated for the required number of days as determined from the retention time, another loading rate was started. Two such loading rates and retention time were used for this experiment as shown in Table 4.5. The operational days were at least equal to the mass retention time. Mass retention time is defined as the active reactor mass (kg VS) divided by the total wet mass fed each day (kg VS), was used to determine the digestion time for each loading rate (Kayhanian & Rich, 1995). However, the working volume of the digester was maintained at approximately 80%. Thus, a proper volatile solid and waster balance was done as described in Chapter 3 section 3.2.2. It means that whatever the amount of volatile solid and water/leachate output were equal to volatile solid and moisture content in the fresh waste going into the reactor (Appendix F).

Table 4.5 Loading schemes for continuous operation

Loading descriptions	Loading rate (kg/day)	Loading rate (Kg VS/m^3.day)	Mass Retention Time (Days)
Loading rate 1	12.5	2	25
Loading rate 2	16	2.5	20

a. Leachate characteristic

Besides biogas composition and production, the stability of the reactor performance was investigated through leachate characteristic analysis. In the anaerobic digestion process, this is particularly true since the mathanogenesis is sensitive to the environmental variations. The first criteria was taken into account was pH value. pH of effluent from leachate indicates the stability of the system and its variation also depends on the buffering capacity itself (Mata-Alvarez 2003). According to the curve in Figure 4.8, pH value remained steady in a very close range from 7.4 to 7.9 during the first 20 days of 2 kg VS/m^3.day loading rate.

One of the main problems in anaerobic digestion process is that it is very sensitive to higher organic loading rate. This overload can be defined as an excess of biodegradable organic matter for the active population capable of digesting it. Thus digester overloaded can be caused by a real excess of organic biodegradable feed, as well as for any circumstance that produces a decrease in the active microorganism concentration. These disturbances mainly affect methanogenic bacteria, whereas acidogenic bacteria which are much more tolerant continue to work, producing more acids. These acids inhibit methane formers (Mata-Alvarez 2003). At the same time, fermentation products which are normally not intermediates can also be formed as an attempt to metabolize the accumulated hydrogen or formate. However, the experimental results of this study indicate the similar problem to the statement. As observed, from day 54, pH value gradually dropped. It is the sign of unstable condition of the system. When pH variation was observed in the system, it is an indication of the unsteady condition occurred as reported by Mata-Alvarez (2003).

pH and alkalinity were the two parameter which always be together for anaerobic process to evaluate the performance of the reactor. These are the quick indicator to explain the stability of the process. The system could not buffer itself and at the same time pH and alkalinity gradually drop as there was a high concentration of carbon dioxide in biogas and which the distribution from a high acidification in the system. As the result, a significant pH alkalinity decreased from day 54 to 71 was observed as illustrated in Figure 4.9. Thus the action taken was to unfed the reactor and observed until steady state condition was recovered. During the unfed period, it was noted that the gradually increased of both pH and alkalinity was found. The maximum value of pH was 7.8 was achieved at day 82. The buffering capacity of the system was also recovered at during the unfed status as a sign of gradually increasing alkalinity value up to 1000 mg/L as $CaCO_3$ at the same day (Table D-2).

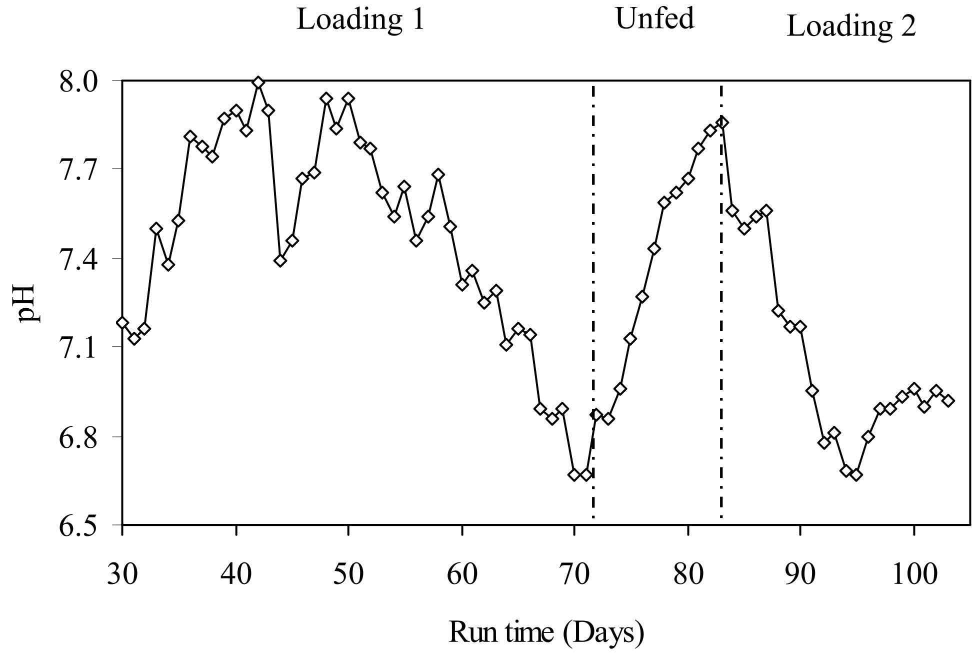

Figure 4. 8 pH variation during draw-feed mode evaluation

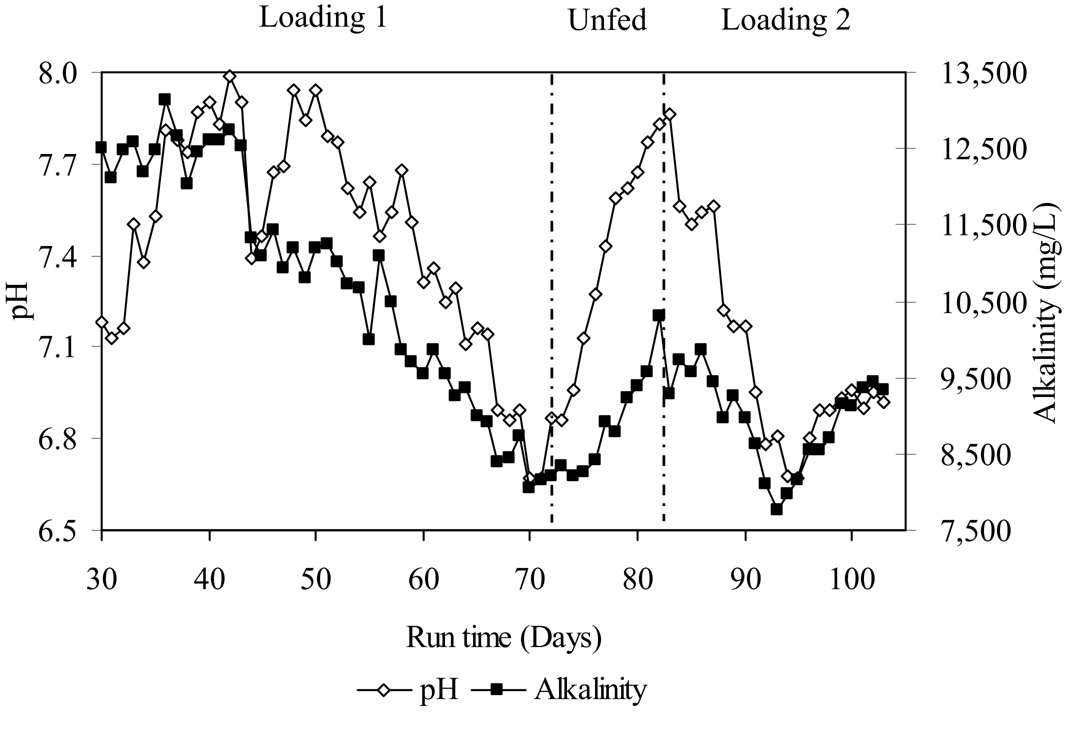

Figure 4.9 pH and alkalinity during continuous feeding

The values of total VFA were also significantly co-related to the pH values. In the similar trend, VFA also fluctuated and increased if pH decreased. It was noticed that for the first 20 days of the loading rate 1 applied, VFA concentration was in the range of 1000-3000 mg/L. It is a sign of no VFA accumulation in the system (Figure 4.10). While pH was in the range of 6.6, VFA accumulation was significantly observed with the highest value of 7500 mg/L at day 61. It is a sign of high acidic condition in the system which may lead to system failure. This was due to the well digested waste was totally removed out from the system for the first 25 days. Thus there was no seed/biomass which is contained the methanogenic population to convert the organic acids produce from acidogenic bacteria. The precaution was taken by unfed the reactor for 10 days. Then, loading rate was resumed at the rate of 2.5 kg VS/m^3.day. Similar result was achieved during loading rate 2 operations. VFA concentration gradually increased and reached a maximum value of 7500 mg/L on day 101. A gradual drop in pH values was observed and pH was adjusted by using commercial grade NaOH.

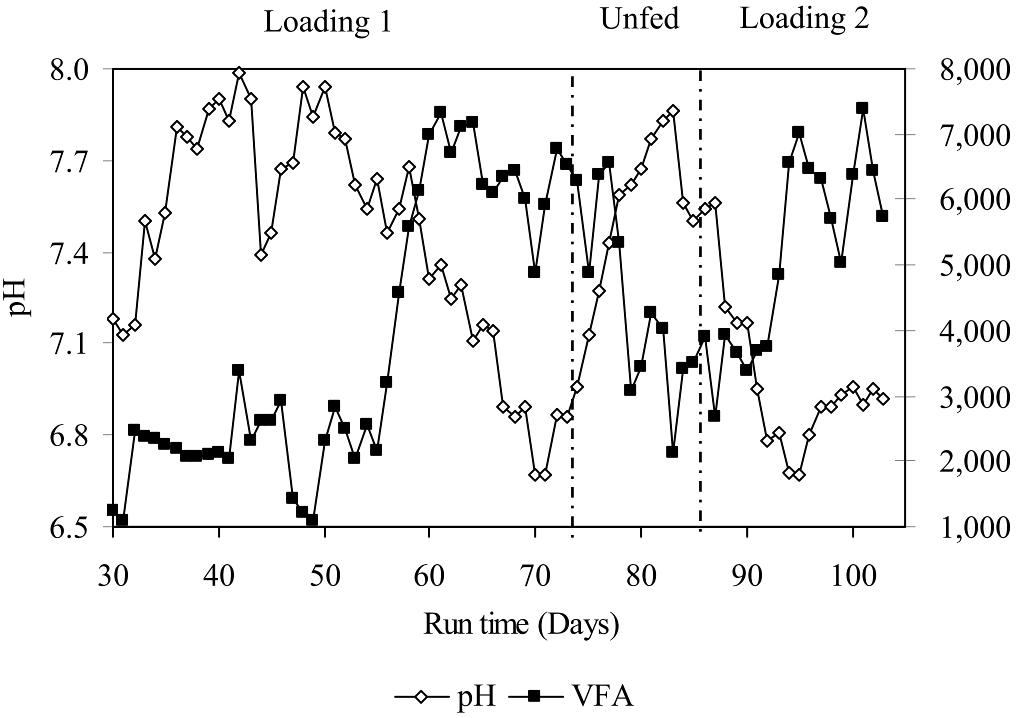

Figure 4.10 pH and VFA during continuous feeding

Figure 4.11 illustrates the daily variation of DOC and VFA during different loading rates as marked by loading rate1 and 2. It should be noted that these two parameters are the indicators of the hydrolysis rate of anaerobic process.

In this continuous loading operation, it was anticipated to get high DOC in leachate which represents the hydrolyzed products from the fresh waste. At the same time, VFA, the product of acidification/hydrolysis, was also the other important parameter influence the anaerobic digestion process. During the first 20 days of loading 1, DOC remained quite stable with little fluctuated value in the range of 5000-7000 mg/L. VFA also showed the same trends. Thus, it was not significantly accumulated to cause any unstable condition as its value was found in the range of 1000-3000 mg/L. This value was found in agreement with Veeken et al (2000) who conducted the study on the effect of pH and VFA on hydrolysis of Organic Solid stated that the maximum organic acid that can be attained in anaerobic digestion is around 3000 mg/L. Similarly, they also confirmed that the complete inhibition of anaerobic digestion was met at VFA around 4000-5000 mg/L. However, when the feeding and withdrawing operation was continued at same rate from day 62 to day 71, both parameters showed increasing trends. This was due to the VFA produced was not utilized by methanogenesis, which lead to less buffering capacity to the system and VFA accumulation. When VFA concentration in the system and carbon dioxide content in biogas simultaneously increase, the process is going to be upset and the acidifying microorganisms are prevailing on the methanogenic ones; therefore, VFAs are accumulating in the system as reported by Mata-Alvarez (2003). Immediate precautionary action was to unfed the reactor. It was noticed that the decreasing trends were obtained from these two indicators. Again, the increasing trends were observed while feeding was resumed at day 83 with loading rate 2 of 2.5 kg VS/m^3.day.

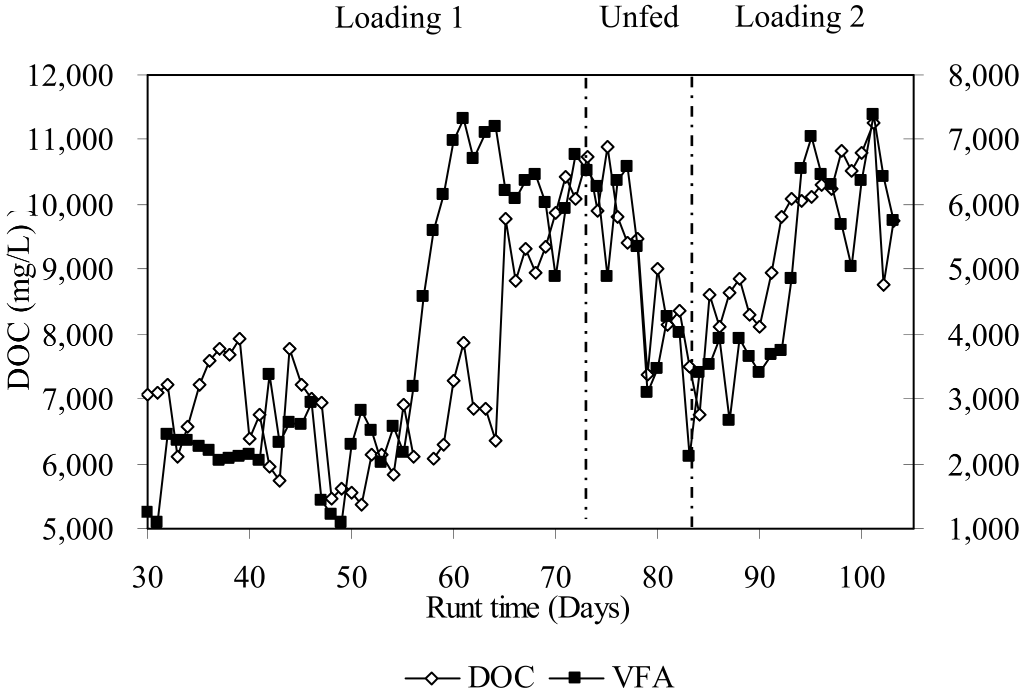

Figure 4.11 Profile of variation of DOC and VFA

The end product of anaerobic degradation of nitrogenous material is ammonia. Protein first converted into amino acid in hydrolysis stage, and then further degraded anaerobically in acidification stage producing ammonia. However, for the waste at this initial stage, the concentration of soluble those nitrogenous materials totally reflex the hydrolysis of nitrogenous materials. The dissolution of readily solubilized fraction of nitrogenous materials in fresh waste also contributes to the concentration of leachate.

Looking into ammonia nitrogen profile in this reactor in Figure 4.12, there is a reasonable effect of reactor configuration on anaerobic degradation of protein. Regardless of the level of TKN, ammonia nitrogen is in the increasing trend from the first day of continuous loading operation begun. Mata-Alvarez (2003) reported that decrease in biogas production contemporary to an increase in carbon dioxide content can indicate an inhibition of the methanogenesis of the system because of the high level of ammonia. As graphically showed, with the continuous operation of loading rate 1 started at day 30, NH_4-N value was 1400mg/L which is still below the inhibit value. A gradual increased in NH_4-N concentration was occurred for longer operation of continuous loading. The maximum value of its concentration was on 2000 mg/L for loading rate 1. At loading rate 2, the continuously increasing in ammonia nitrogen still observed and reached maximum value of 2300 mg/L at the last day of loading 2. This finding was similar to Adhikari (2006) who stated that with increase in mass loading, increasing trend in ammonia concentration was noted. However, it appeared that the inhibitory was happened as this work was operated in thermophilic condition as mention by Mtz-Viturtia et al. (1995) who conduct the study on anaerobic digestion of fruit and vegetable wastes recommends that one-phase system for residues with a C/N ratio above 15. Ammonia toxicity can increase if the digester is operated at thermophilic conditions, due to the ammonia solubility and to the displacement of the ammonium-ammonia equilibrium to towards the unionized form.

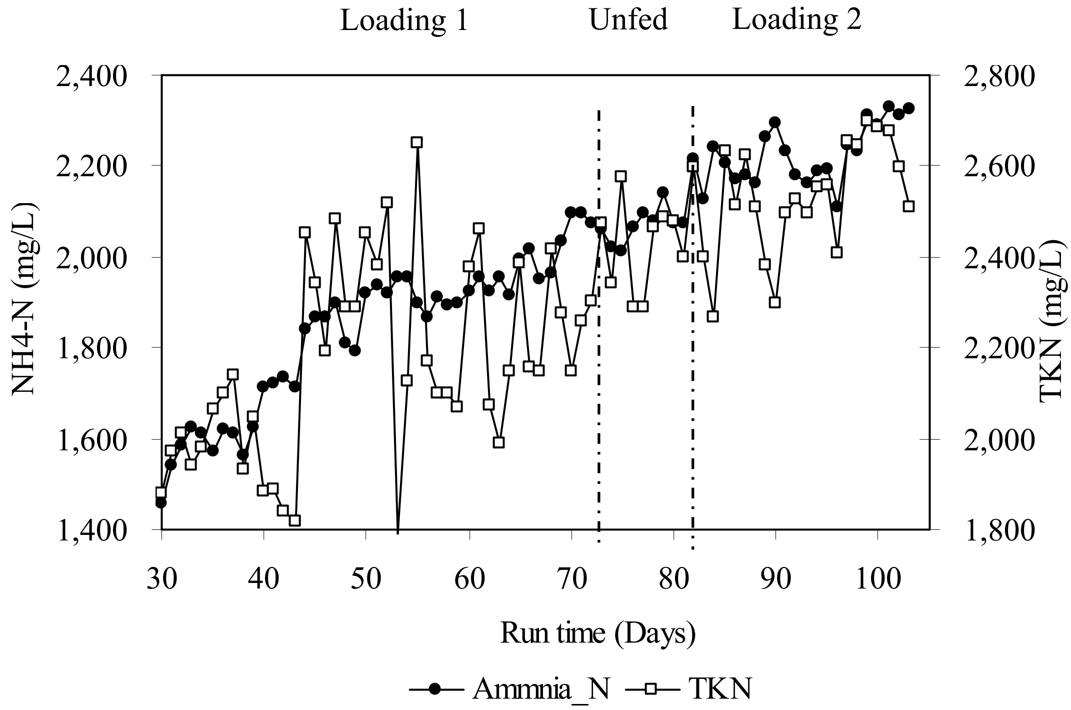

Figure 4.12 Ammonia nitrogen and TKN

b. Biogas production and composition

Biogas production was monitored daily. 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 as well as production to various loading rates condition.

The experimental results showed the fluctuation of daily biogas generated during both feeding rates as graphically presented in Figure 4.13. Likewise, in the unfed condition, a very close range of biogas produced was observed from day 72 to day 82 with the amount of approximately 170L/day. However, cumulative of biogas was obtained in the straight pattern indication of biogas remain generated daily.

Methane concentration in biogas was observed below 50% of biogas produced for both feeding rates applied except the first three days of loading and unfed condition (Figure 4.14). 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 stability 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 not only produced from acidification of the system, it was also the production of aerobic reaction took place inside the reactor. This problem was occurred during the draw-feed mode process by which there was a chance of air can go inside the reactor due to the reactor configuration itself was not air tight to be operated under anaerobic condition with continuous operation process. This statement can be proofed by comparing the methane concentration during the first few days of operation and in the unfed condition. It was noted that the gradually decreased from 60% at day 30 to approximately 30% at day 71 was achieved. For this reason, the indication of unsteady state condition of the reactor was occurred. Because of this problem, reactor was kept unfed till methane contained in biogas reached above 50%.

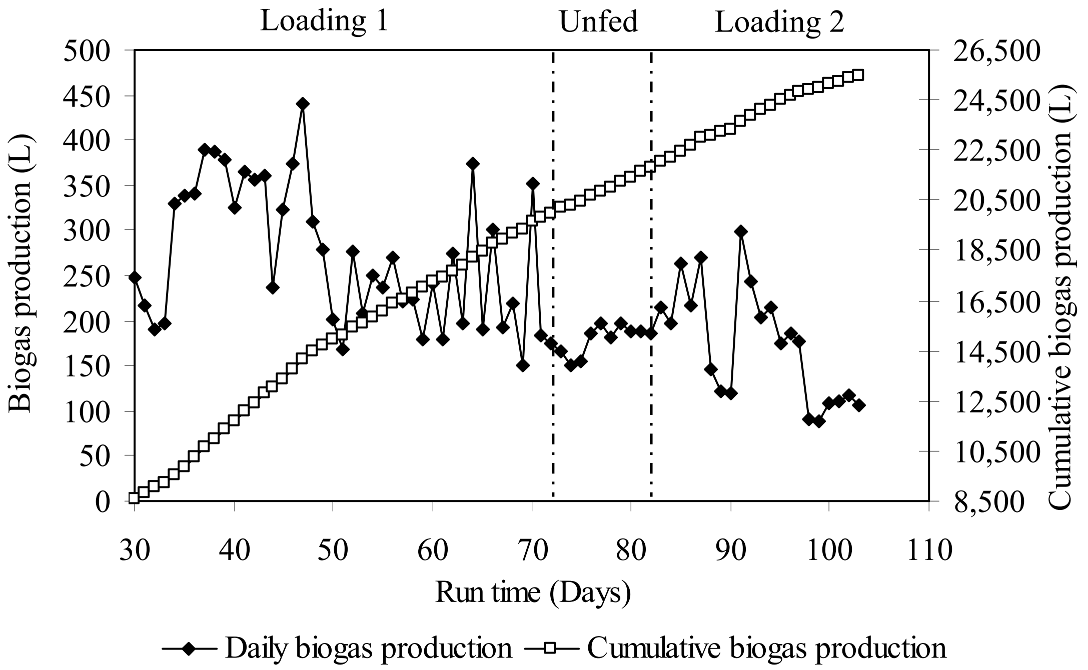

Figure 4.13 Profile of biogas production during continuous operation

The withdrawing and feeding mode of operation with loading rate 2 (2.5 kg VS/m^3.day was resumed at day 83 as the methane content reached maximum value of around 65% at day. Unfortunately, the same problem was occurred. Methane concentration was even far below 50%, around 15-30% and carbon dioxide was very high compared to loading rate 1. This was due to the same problem as in the previous description as well as inactivated of methanogenic bacteria due to a very high acidic condition.

4.1.4 Overall process assessment

Anaerobic digestion process which used in this research is relatively a simple option. Nevertheless, operating the pilot scale equipment for all most haft a year 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 rate and assess each rate in terms of biogas yield, quality as well as the quantity. This is because of the reactor configuration itself was come up with the technical design problems. However, for the single purpose of evaluating this system on the effect of loading rate, VS reduction, biogas composition and specific gas production were taken into account as the indicators to assess the reactor performance and efficiency of each loading rate.

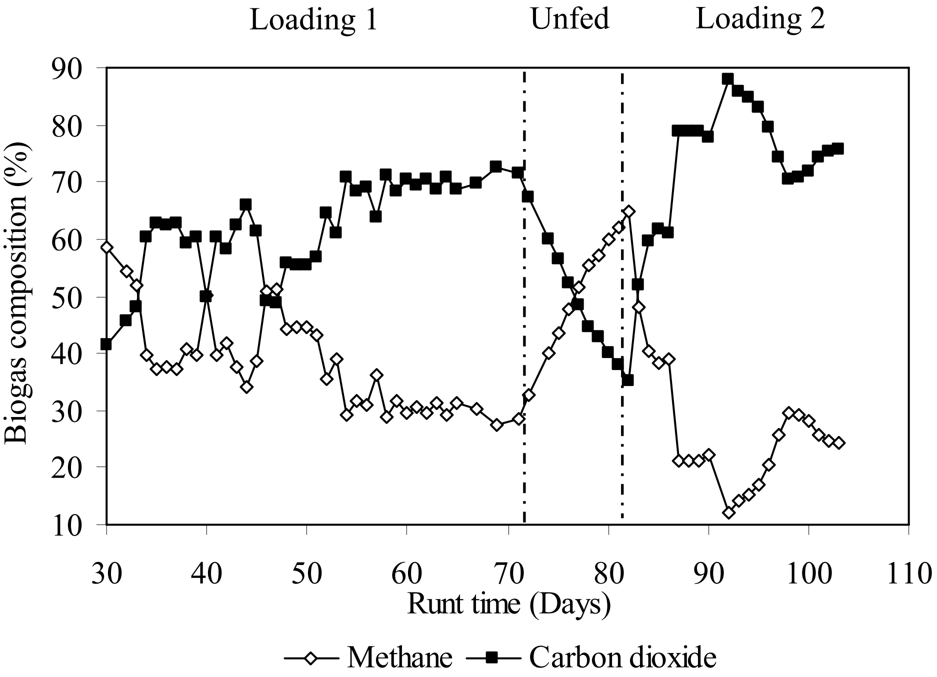

Figure 4.14 Profile of biogas composition during continuous operation

To give a comparison of each loading, the profile of volume of gas production rate per reactor volume was plotted in Figure 4.15. It was clearly demonstrated that the highest biogas production is 0.44 m^3/day per m^3 reactor volume was obtained for loading rate 1 with the OLR of 2 kgVS/m^3.day. Likewise, the lower value of 0.31 L/day per reactor volume was obtained with the higher OLR of 2.5 kgVS/m^3.day. This finding is in opposite agreement with Castillo et al. (2006) who reported the increased gas production rate with decreased retention time. This was due to air leaking problem caused by reactor configuration itself.

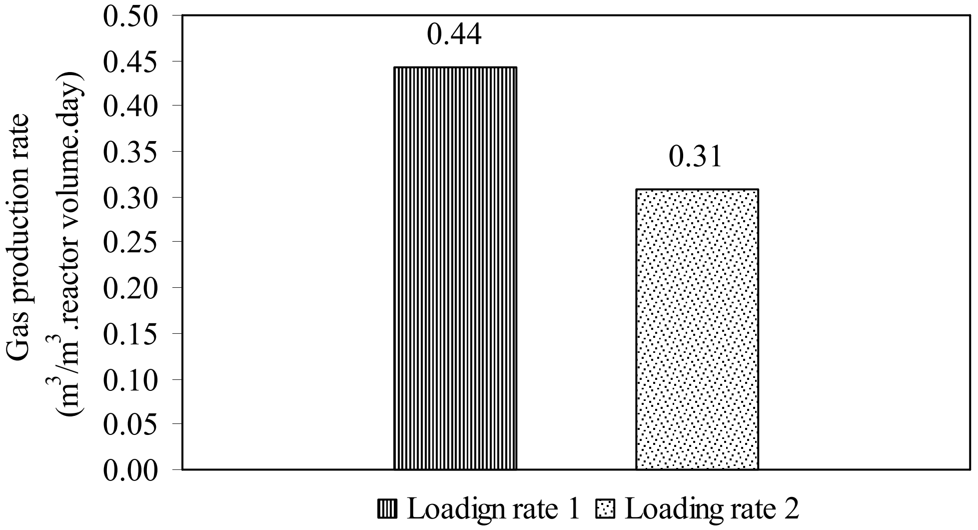

Figure 4.15 Profile of gas production rate for various loading

With respect to compare these two loading rate in term of gas production, cumulative gas production was also plotted as showed in Figure 4.16 for various loading rate. As gradual increased in loading rate 1 of 2 kg VS/m^3.day to loading rate 2 of 2.5 kg VS/m^3.day, accumulative biogas production was decreased. Corresponding to Figure 4.15, the highest biogas production was obtained from the loading rate 1. On the other hand, there is no any increment was observed for biogas production rate in loading rate 2. Additionally, the slope even slightly dropped as illustrated in Figure 4.16.

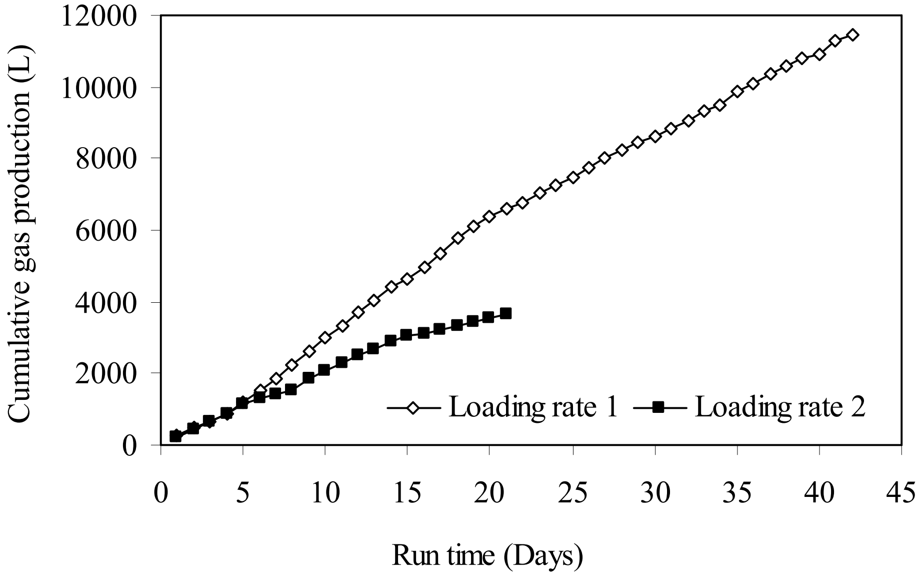

Figure 4.16 Cumulative gas yield for different loading rates

For further investigation, specific gas production for these two loading rated was consider and graphically illustrated in Figure 4.17. The highest specific gas production was loading rate 1 of 401 L/kgVS $_{\text{removed}}$.

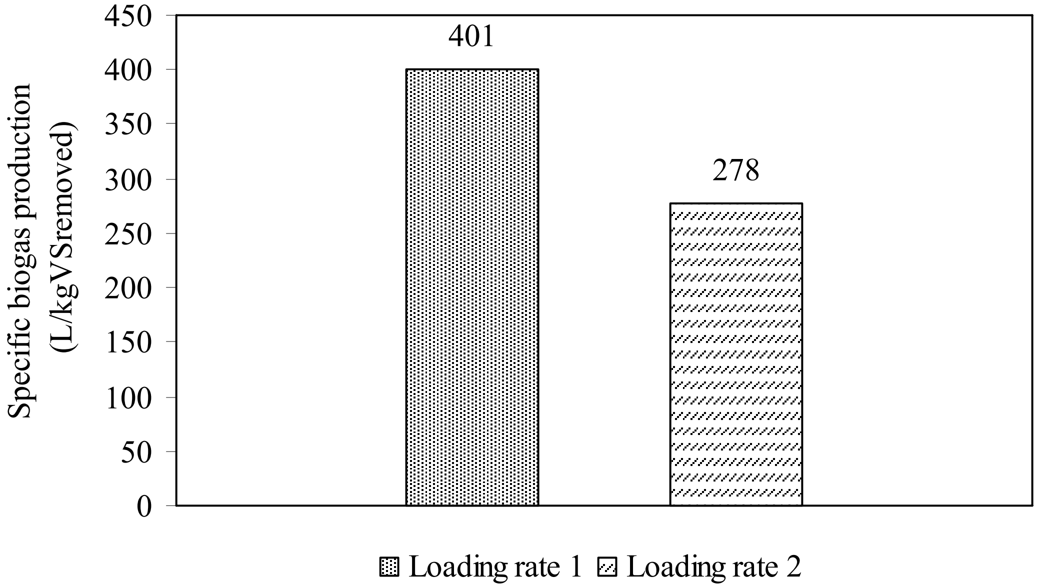

Figure 4.17 Profile of Specific gas production for various loading rates condition

Figure 4.18 presents the specific methane yields in these two loading schemes. The specific biogas, methane gas in particular, increased considerably from loading rate 1 to loading rate 2. The specific methane yield obtained was 140.35 and 62.55 L CH_4/kg VS for loading rate 1 and 2, respectively. This value correspondence to 47.57% and 21.20%

process efficiency calculated based on the laboratory BMP assay (295 L CH_4/kg VS at STP).

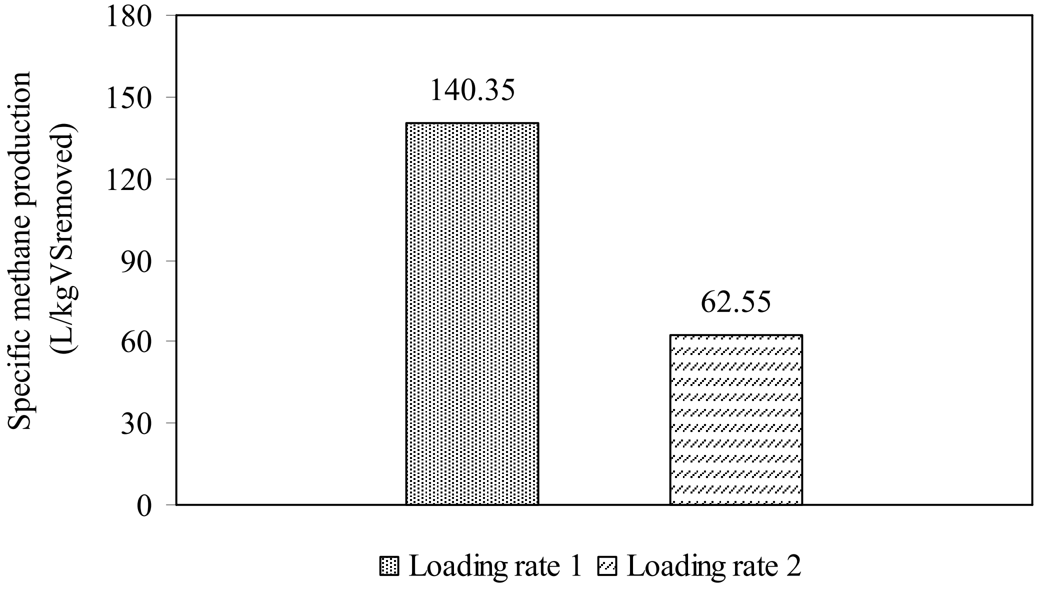

Figure 4.18 Methane Production rate for various loading

Volatile solid reduction was taken in to account as well to evaluate the reactor performance and stability of the digestaste. VS degradation value of 51% was achieved when operating with loading rate 1 of 2.5 kg VS/m^3.day. On the other hand, while loading rate was increased, only 43.22% volatile solid reductions were obtained as illustrated in Figure 4.18 (Appendix E). Comparably, these VS reduction was lower with result found by Castillo et al. (2006) who reported that VS reduction of 77.1% and 74.1% were obtained with the digestion time of 25 and 21 days respectively. By far different results in this study were due the problem mention earlier in this section that the reactor configuration itself was not fully anaerobic and made the process difficult to operate continuously. However, the result still in line with the same author since they also mentioned that VS removal efficiency is decreased with decreased the retention time.

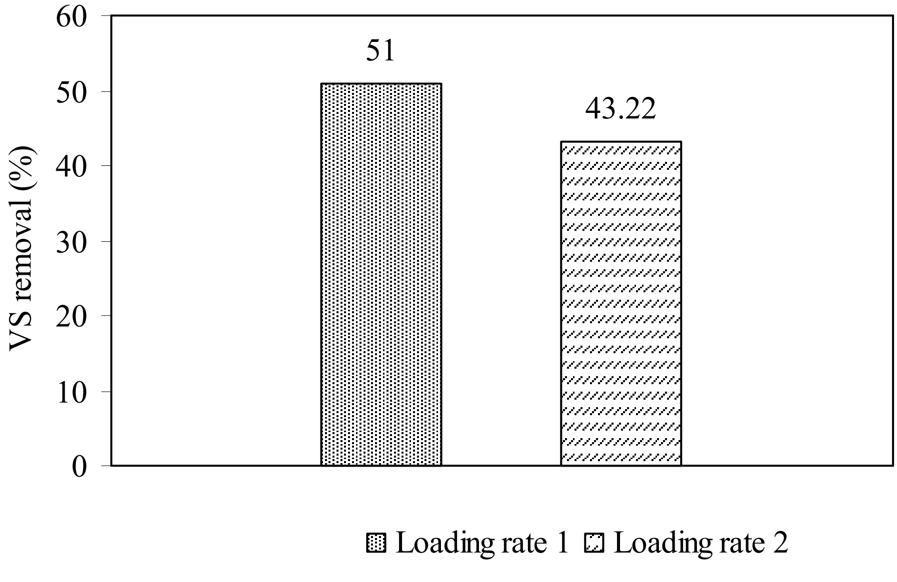

Figure 4.19 VS degradation for various loading rates

Heavy metals in solid waste, effluent leachate and digestate waste were also conducted to meet one of the main objectives of this research. Metal solubility in the leachate increase as pH decreases. The highest metal concentrations are observed during the acid formation phase of waste stabilization when pH values are low. Therefore, methanogenic conditions and neutral pH in anaerobic system resulted in lower heavy metals leaching from the system as reported by Erses & Onay (2003). As reported by O'Brien (2005), on average, heavy metal concentrations in leachate have been reported in numerous recent studies to be relatively low. However, in the presence of sulfides, most of the heavy metals except chromium form extremely insoluble sulfide salts. Table 4.6 illustrates the heavy metals concentration in leachate. This result found Zn has a highest leaching potential as in line with the reported by Baun & Christensen (2004).

Table 4.6 Heavy metals concentration in leachate during continuous feeding

Heavy metals	Concentration (μg/L)		
	Runt time (Day 60)	Run time (Day 90)	Run time (Day 103)
Cadmium (Cd)	5.24	0.91	3.75
Lead (Pb)	0	20.48	8.56
Zinc (Zn)	632.55	509.83	313.67
Copper (Cu)	536.79	326.80	139.49
Chromium (Cr)	44.82	17.47	3.78
Nickel (Ni)	157.27	112.74	47.77
Manganese (Mn)	1124.30	1018.71	555.47
Mercury (Hg)	1.37	1.104	0.954

4.1.5 Heavy metals balance

To meet with the objective of this study, an attempt to investigate the fate of heavy metals after digestion was done by using mass balance analysis. The mass balances of heavy metals were calculated from their concentrations in solid waste, inoculum, leachate and digestate waste. Mass balance calculations were done for the whole operation of this experiment. Table 4.7 presents the mean concentration of heavy metals that enter and exit the anaerobic system. In theory, there should be very good accordance between the input and the output loads for conservative pollutants like metals. The ratio [(IN – OUT)]/IN *100 equals the percentage of loss or gain for each determinant (Karvelas et al. 2003). Table 4.7 shows that there was less chance of heavy metals solubilization in the leachate. It was noted that heavy metals concentration leaching in leachate is calculated based on average value.

Table 4.8 illustrate the heavy metals input and withdraw for 103 operational days. It is noted that two sources of heavy metals input were solid waste substrate and inoculum. The significant highest heavy metal loaded was Zn with the value of 12,897 mg, and followed by Cu with value of 4115.74 mg.

Table 4.7 Heavy metals concentration in various samples

Heavy metals	Heavy metals in Solid waste (mg/kg DM)	Heavy metals in leachate (µg/L)	Heavy metals in digestate (mg/kg DM)
Cadmium (Cd)	0.25	3.11	0.64
Lead (Pb)	0	6.06	0
Zinc (Zn)	72.24	500.79	105.74
Copper (Cu)	15.29	308.45	50.66
Chromium (Cr)	7.36	34.81	13.88
Nickel (Ni)	4.10	184.40	12.16
Manganese (Mn)	88.10	879.53	86
Mercury (Hg)	0.036	0.98	0.0345

Table 4.8 Cumulative heavy metal loaded

Heavy metals	Heavy metals input (mg)		
	Solid waste (139.08 kg TS)	Inoculum 36.945 kg TS)	Total
Cadmium (Cd)	45.04	16.63	61.67
Lead (Pb)	0	5.83	5.83
Zinc (Zn)	10,846.56	2,050.45	12,897
Copper (Cu)	2,268.49	1,847.25	4,115.74
Chromium (Cr)	1,016.90	184.73	1,201.63
Nickel (Ni)	612.18	461.81	1,073.99
Manganese (Mn)	12,252.94	2029.8	14,282.74
Mercury (Hg)	5.01	-	5.01

Based on the analysis result, cumulative heavy metals withdrawal from the system was Zn and Cu for both leachate and digestate waste (Table 4.9). Additionally, the leaching potential of all heavy metals through leachate was less. It means that it potentially cumulated in the digested was due the precipitation reaction by sulfide formed from sulfate reduction. Thus, it was concluded that there the deduction of heavy metals loaded from anaerobic digestion process depends on sulfide concentration (Erses & Onay 2003).

Table 4.9 Cumulative heavy metal output

Heavy metals	Heavy metals output (mg)			
	Cumulative in digester	leachate (571.77 L)	Digestate (70.25 kg TS)	Total
Cadmium (Cd)	8.63	1.78	44.96	55.37
Lead (Pb)	0	5.46	0	5.46
Zinc (Zn)	2,070.60	286.34	7,428.24	9,785.18
Copper (Cu)	79.51	176.36	3,839.87	4,095.74
Chromium (Cr)	194.78	19.90	9,75.53	1,190.21
Nickel (Ni)	117.26	99.44	854.24	1,070.94
Manganese (Mn)	3129.31	502.88	6041.5	9646.69
Mercury (Hg)	0.96	0.56	3.05	4.57

Figure 4.19 illustrates the heavy metals removal efficiency from anaerobic digestion process for 103 operational days. The precipitation of nickel, copper, and chromium were lower than the other metals. The precipitation efficiency ranged between 0.28, 0.49 and 0.95% for these metals, respectively. The precipitation efficiency of manganese in the reactor was much higher than the other metals with the removal percentage of 32.46 followed by Zn with the value of 23.13 %. It was noted that all heavy metals was deducted due to the formation of sulfide from sulfate which provides heavy metal precipitation (Erses & Onay 2003). The measurements of sulfate, and sulfide also confirmed the attenuation of the heavy metals during this period.

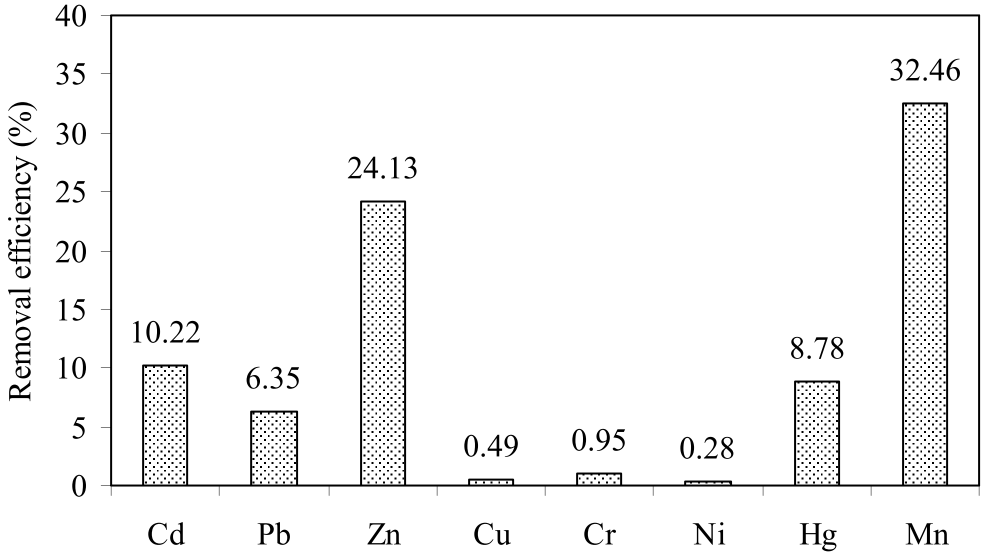

Figure 4.20 Profile of removal efficiency of selected heavy metals

4.2 Bio-chemical Methane Potential (BMP)

The BMP test procedure presented in Hansen et al., (2004) was used in this study to determine the methane potential from OFMSW. It was used to determine the maximum methane produced from the certain amount of volatile solid. It is important to emphasize that in this study, incubation at optimum thermophilic temperature (55°C) for 50 days was found sufficient to ensure the degradation of degradable material contained in the substrate as in line with Hansen et al. (2004) who studied the BMP test of separated organic household waste. Likewise, Juanga. (2005), who also conducted her studied on OFMSW in mesophlilic condition for 100 days found that it was sufficient to ensure the biodegradation of substrate contained in the waste. Thus, the conclusion could be drawn that the BMP test is not depend on temperature, incubating at lower temperature may influence the incubation time but the BMP of the waste would just be the same.

The test was conducted in 2.5 L reactors sealed with its cover and rubber stopper to make it easy sampling. Each reactor contained 2 g VS of substrate and 400 mL of anaerobic sludge as the inoculum. For each blank reactor runs, contains only 100 mL of DI water and 400 mL of anaerobic sludge, was set to measure the gas production of seeding. During the experiments in progress, the sample bottles were shaken in incubator at 55ºC. To remove the amount of gas production, a 60 mL gas syringe was used to avoid too high pressure in side the reactor. The amount of gas production from the OFMSW sample degradation was calculated by subtracting methane production determined from blank reactor (Appendix G). Figure 4.21 represents the methane potential of OFMSW together with blank reactor.

The methane production form inoculum was subtracted from methane production of waste sample to get the corrected value of methane potential (Figure 4.22). The cumulative volume of methane was presented. Adhikari (2006) conducted BMP tests on OFMSW as well, and the potential volume of methane was found to be 300 L/kg VS which is similar to the result obtained in this research.

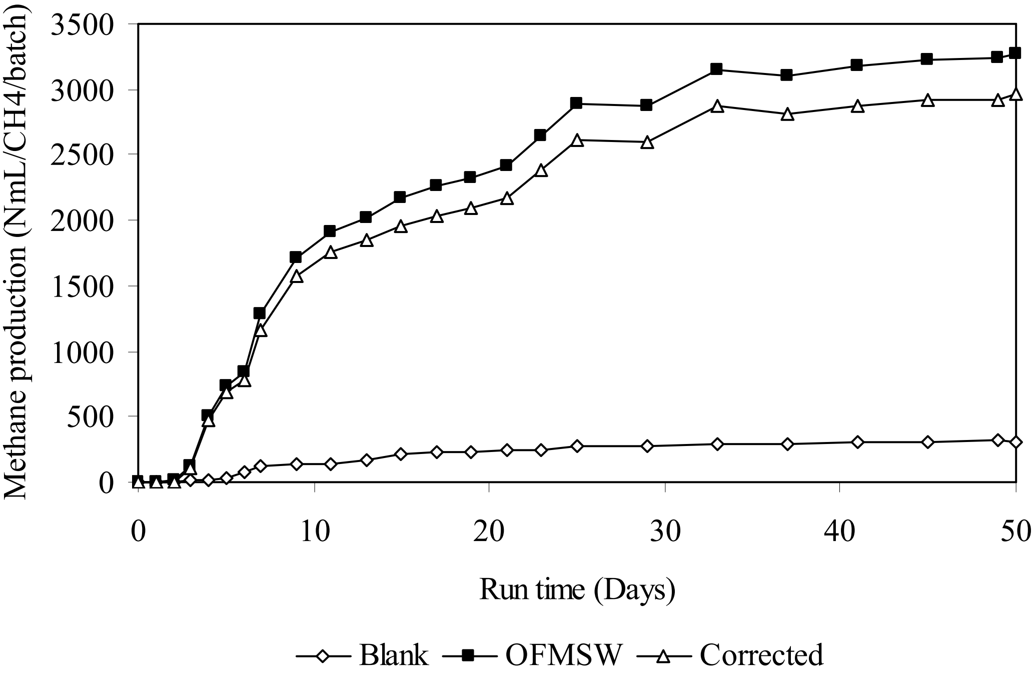

Figure 4.21 Cumulative methane production BMP reactors

The volume of methane production is all converted to standard temperature and pressure (STP) conditions. It is concluded from Figure 4.23 that methane potential increased rapidly and stabilized at day 50. It is in line with Hansen et al. (2004) who reported that full degradation of organic matter at thermophilic condition is 50 days. Figure 4.21 depicted the corrected cumulative methane production at STP.

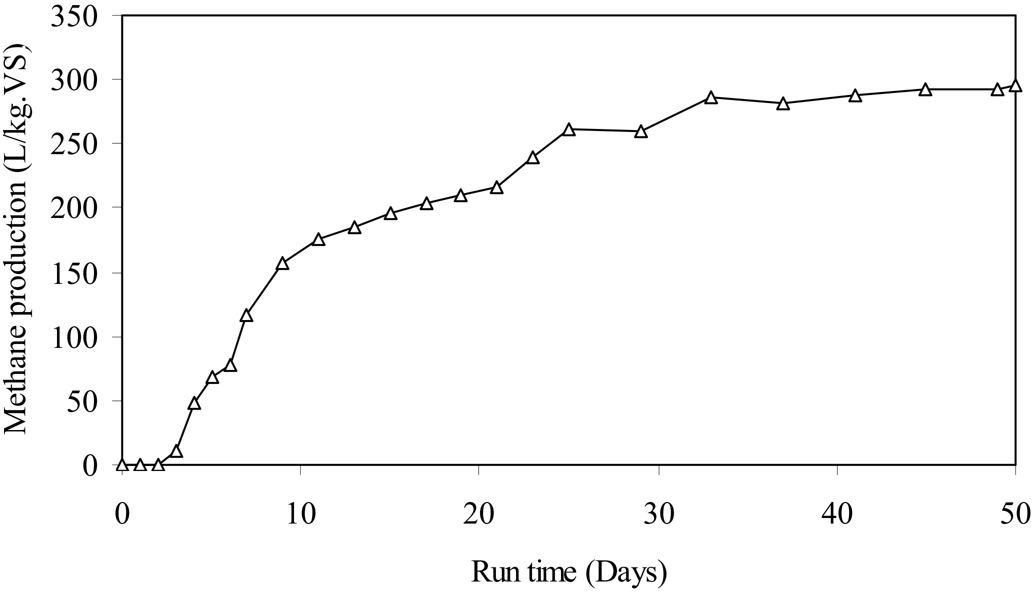

Figure 4.22 Corrected Cumulative methane potential (Lab scale) at STP

4.3 Digestate quality

Apart from biogas, anaerobic digestion also produces solid and liquid by-products which can have values as fertilizer or soil amendment. The amount, quality and nature of these products will depend on the quality of the MSW feedstock, the method of digestion (wet or dry) and the extent of the post treatment refining processes. The main product at dry digestion process is as 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 4.10 illustrates the nitrogen, phosphorus, potassium, and carbon value in digestate sample from this research. Regarding these analysis results as obtained, the anaerobic digestion reduced the nitrogen content in feedstock. Likewise, the increasing the phosphorus and potassium was found. A decrease of nitrogen concentration in the digestate was presumably due to bio-conversion to ammonia gas and subsequent volatilization. For potassium and phosphorus, were higher due to the fact that some solid have been converted to biogas, resulting in higher nutrient concentration. This research has found similar result to Kayhanian & Rich, 1995. 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 landscaping efforts or even crop production**,** in addition to the recovery of energy because 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 4.10.

Table 4.10 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	1.09	0.65	0.65	22.75	20.87	11.16

[*] Rattanaoudom, 2005, cited source: Land development department

[**] EUTITS standards (European Association of Waste Thermal Treatment Companies for Specialized Waste)

Another important criterion is heavy metals concentration in the digestate sample. When treating wastes there is also the potential to have pollutants in the feedstock that may contain heavy metals. Heavy metals cannot be destroyed and thus the only control is to ensure that the feedstock are as clean as possible (IEA, 2001) Selection of feedstock can reduce heavy metals to acceptable levels. When treating MSW, green waste and source separated bio-waste provides the cleanest feedstock. Within the process, only a few process designs offer the high removal efficiency of heavy metals. These based on the two or multiphase systems where metals in solution can be precipitated out in the liquid phase as confirmed by IEA (2001). Table 4.11 presents the heavy metals concentration in digested waste. It was noted that all the selected heavy metals have felled below the standards both WHO (proposed) and Dutch.

Moreover, the market value of these compost type products as a soil conditioner or fertilizer depends on the compliance with the governing quality standards especially with respect to the concentration of heavy metals, but also on the guarantee of a pathogen and seed free product. Digestates from the organic fraction of source separated MSW can comply with the quality standards much more easily as reported by IEA (2001). Thermophilic (55°C) digestion provides high levels of sanitization within relatively short times (6-10 hours). This control of pathogens is essential in the control of disease on farms and will kill other viruses, parasites and bacteria that may affect other uses of the digestate as reported by Biocycle (1996). In general, most studies have shown that anaerobic digestion results in reduction in numbers of pathogenic organisms (Berg and Berman 1980; Engeli et al 1993; Stukenberg et al 1994; Bendixen 1994 cite in Chynoweth, D.P, & Pullammanappallil, P. (2005). Destruction of these organisms is related to temperature and is only effective at thermophilic temperatures. Bendixen (1994) cited in Chynoweth & Pullammanappallil (2005) showed that most pathogens were killed in thermophilic solid waste digesters, including bacteria, viruses, and parasites. These results point to the advantages of anaerobic digestion and thermophilic temperatures for effective pathogen reduction as reported by Chynoweth & Pullammanappallil (2005). Since the operation was in thermophilic condition, there was less chance of pathogen to be contaminated in the digestate material.

Despite the fact that digestate residues after anaerobic digestion matched with the standards to be used as the soil conditioner, another important note from the digestate is the potential of using as RDFs since it has a high calorific value. From this the laboratory analysis for the digestae in this study, the calorific value was 11.15 MJ/kg which is similar to Gendebien et al. (2003) who reported that the net calorific value of RDF are fairly consistent (12-16 MJ/kg) for house hold waste which would fail the EUTITS (European Association of Waste Thermal Treatment Companies for Specialized Waste) requirements for secondary fuels used for clinker production. This may due to the feedstock waste was hand-sorted. However, the stabilized residue still has the potential to be used as refuse derived fuel (RDF) if mixing with industrial waste can be done because industrial waste has very high calorific value ranging from 18-21 MJ/kg.

Table 4.11 Heavy metals analysis of digestate

	Heavy metals (mg/kg DM)						
	Cd	Cr	Cu	Pb	Ni	Zn	Hg
Dutch standard (Clean compost***)	1	50	60	100	20	200	0.3
Dutch standard (Very Clean compost***)	0.7	50	25	65	10	75	0.3
WHO standards (Proposed)****	3	50	80	150	50	300	-
Digestate	0.64	13.88	54.66	0	12.16	105.74	0.0345

*** Chynoweth & Pullammanappallil (2005)

**** Rattanaoudom, 2005, cited source: Compost-Consulting Development (2004)

4.4 Energy Production and Consumption

Anaerobic digestion process is an effective method for waste management strategy for getting rid of organic material and at the same time it could generates much energy. Biogas produced by the AD process is quite similar to “natural” gas as it is extracted from the wellhead. The particular characteristics of methane and the principal component of biogas, make it an excellent fuel for many uses. However, the actual amount of energy recovery from the solid waste was depending on the efficiency of the conversion process.

In this study, the energy balance was taken into account only during the start-up operation (Phase 1). This was due to the biogas generated in loading operation (continuous process) was low methane content (less than 50%). The main purpose of observing the energy balance in this experiment is to highlight the energy consumed by this thermophilic reactor as well as to determine the potential of energy production from the substrate itself. It was notice that two main stages of energy consumption from this continuous operation were feedstock preparation (shredding) and heating process to maintain thermophilic condition. Table 4.12 represents the energy balance study from this thermophilic continuous operation reactor.

Table 4.12 Energy balance analysis

Description	Total VS input (kg)	Total biogas production (L)	Energy produced (MJ)	Energy consumed (MJ)	Energy gained (MJ)	Energy gained (MJ/kgVS
Continuous	29.24	6,915	144.52	48.36	96.19	3.28

In this operational process, the energy was accounted for heating and shredding only. Figure 4.22 shows the energy expensed to produce the biogas in percentage. It is interesting to note that shredding consumed of 90% of total energy, the remaining energy of 10% being utilized by heating process.

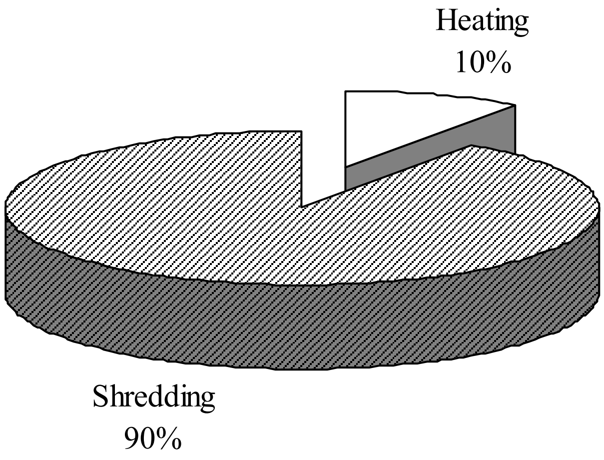

Figure 4.23 Profile of energy consumption for the process

Energy surplus from this start up process was estimated to be 67% (Figure 4.23) (the detail calculations are attached in Appendix B) compared to 75% in the study by Adhikari (2006) in vertical continuous operation digester. This is obvious as the system was not being able to maintain the steady state condition due to the reactor configuration itself. However, it is noted that the start up operation still has a net energy gaining which can produce sufficient amount of surplus energy from its operation for economically value.

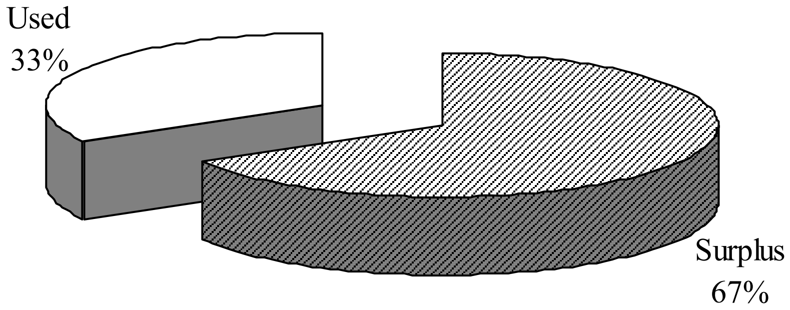

Figure 4.24 Profile of energy balance of the process

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

In this study, pilot scale of anaerobic digestion to treat OFMSW was conducted. A horizontal inclined anaerobic reactor was designed and operated under continuous mode. An attempt to optimize the process was done by increasing the loading rate at different digestion time. The conclusions drawn based on results from this study are the following:

An effective start-up the anaerobic digestion without inoculum and substrate acclimatization can be also done successfully. A gradual increase from mesophilic condition at the rate of 2°C per day reaching thermophilic was found satisfactory, resulting in no any affect to biogas production and composition.

This study found that as the loading rate increased, the biogas production decreased. The methane biogas production rate of 140.35 L/kgVS of reactor were achieved from loading rate 1 of 2 kg VS/m^3.day. However, when loading was increased to 2.5 kg VS/m^3.day, the significant deterioration of biogas composition as well as production was observed. Thus only 62.55 CH_4 L/kgVS reactor were obtained from this loading 2.

Volatile solid degradation of 51% was noticed during the loading 1 operation compared to 43.22% in loading 2.

Heavy metals balance revealed that relatively low amount of heavy metals was leached out of the reactor. This low reduction percentage of heavy metals is due to the precipitation of sulfides formed from sulfate reduction.

The experimental results showed that the end products of anaerobic digestion are relatively stable. By analyzing of nutrient content in the residues, it was clearly shows that this digestate has a potential to be used as soil conditioner since its nitrogen, phosphorus and potassium meet with the Thai guideline by Land Development Department. Alternatively, calorific value of digestate was found 11.15 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 the start-up operation. It shows an energy surplus from the system with 67% energy gain.

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 by products. However, an attempt on the optimization of continuous process for this experiment was not completely achieved since the highest VS reduction obtained is only 51%. Therefore, the new concept was envisioned that may possibly improve the process for further study and was not able to apply due to time constraints. Thus, the following aspects can be taken as the recommendations for future study of such anaerobic digester;

5.2.1 Reactor configuration and modification

The major problem encountered in this study was the low efficiency of methane concentration in biogas generated during the phase 2 of operation (continuous process). It was proven by other parameters such as pH, alkalinity, ammonia nitrogen, and VFA that during the first few days of operation and unfed condition, the reactor performed in the stable condition. However, the produced biogas still content low percentage of methane (below 50%). Later, the problem on the drop of methane concentration was found due to the traced on the technical problem on reactor configuration and not with the process itself. Therefore, the modifications of the reactor are recommended for better performance of this digester in future study. The following options can be drawn for this digester modifications based in this study observations;

Option 1: First of all, feeding part of this reactor should be adjusted to be smaller as the existing feeding hopper is bigger. Additionally, the removable plate at this part should be replaced by the bigger valve, to close it easily and quickly letting no chance of air to go inside the reactor. The modification of the withdrawal section should be done in such a way that make leachate can be drained from the system faster and no chance of oxygen dissolve in leachate. Moreover, the goal of making 30°C inclined type reactor was to facilitate the removal to the digestate easier. However, this experiment still faced the problem with the difficulty of taking the residue out of the system. Another thing is the inclination may cause the low pressure at the bottom of the digester, during the withdrawing process. To make a balance, higher pressure outside the system can make air filtration easily go to the reactor through feeding section. Thus, inclination was found not necessary.

Option 2: The reactor used for the continuous digestion of OFMSW in this research represented a one stage system in which acidogens and methanogens are working together in the same vessel. The possible limiting factors are biomass concentration, mass transfer rate substrate to bacteria, or accumulation of inhibitory substances. These results in a rise of residual VFA and accumulate in the system, thus inhibit the methanogenesis. Especially, the design of this reactor is not full air tight during the withdrawing the waste for the continuous operation. Thus, the feeding and withdrawing on the same reactor vessel in this research found not efficient. Hence, the separating anaerobic process into two phases, i.e., acidification and methanogenesis, facilitate the optimal growth for non-methanogenic and methanogenic bacteria. With these two steps occurring in distinct reactors, it becomes possible to increase the rate of methanogenesis. Based on these consideration, a semi-continuous of a hybrid anaerobic solid-liquid (HASL) bioreactor for solid digestion should be applied as the next research direction for the study. HASL is an enhanced two phase system with a leachate recycles reactor as the acidification phase and an upflow anaerobic sludge blanket (UASB) reactor as the methanoenesis phase. Based on the finding from the phase 1 of this study, the performance of this digester was well if there is not any feeding and withdrawing was applied. Hence, this reactor can serve as the acidification reactor without any justification required. A new methanization reactor is required to make this two stages system run.

5.2.2 Feeding frequency

Instead of feeding once a day, the continuous operation should be tried with feeding twice a day. It may help decreasing the shock caused by a great amount of fresh waste substrate in the bio-digester. In this was, it may be able to produce a more constant methane production rate and new stable with shorter digestion time, thus higher loading rate.

5.2.3 Co-digestion

Several characteristics make anaerobic digestion of the OFMSW difficult. By selecting co-digestion with several other waste types it will be possible to optimize the anaerobic process. The co-digestion concept involves the treatment of several waste types in a single treatment facility. By combining many types of waste it will be possible to treat a wider range of organic waste types by the anaerobic digestion process. As reported by Mata-Alvarez (2003), the co-digestion enable the treatment of organic waste with a higher biogas potential that make the operation of biogas plants more economically feasible. Co-digestion of OFMSW with manure in 50% (VS/VS) gives a beneficial stabilization effect (Hartmann & Ahring, 2005).

5.2.4 Waste stabilization confirmation

Biochemical Methane Potential test (BMP), besides using OFMSW as a substrate for methane production, a try should be conducted by utilizing the digestate waste obtained from this operation as a substrate, to confirm whether further degradation is achievable or not.

5.2.5 Residue digestate utilization

The residue after digestion is rich in nutrients and this is suitable to be used as fertilizer. The application of this digested material to the selected plants should be tried for further confirmation of the effectiveness of this residue.

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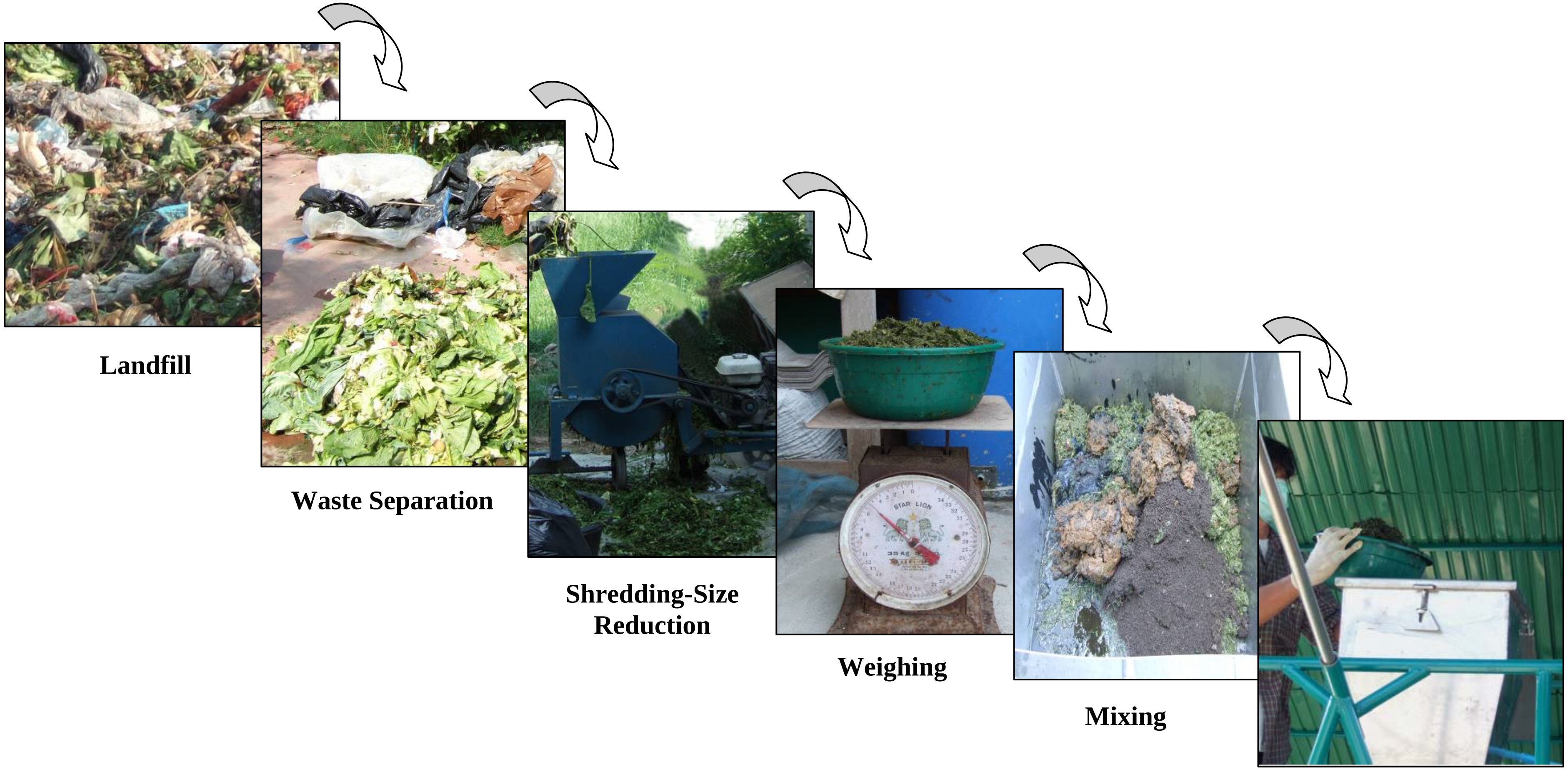
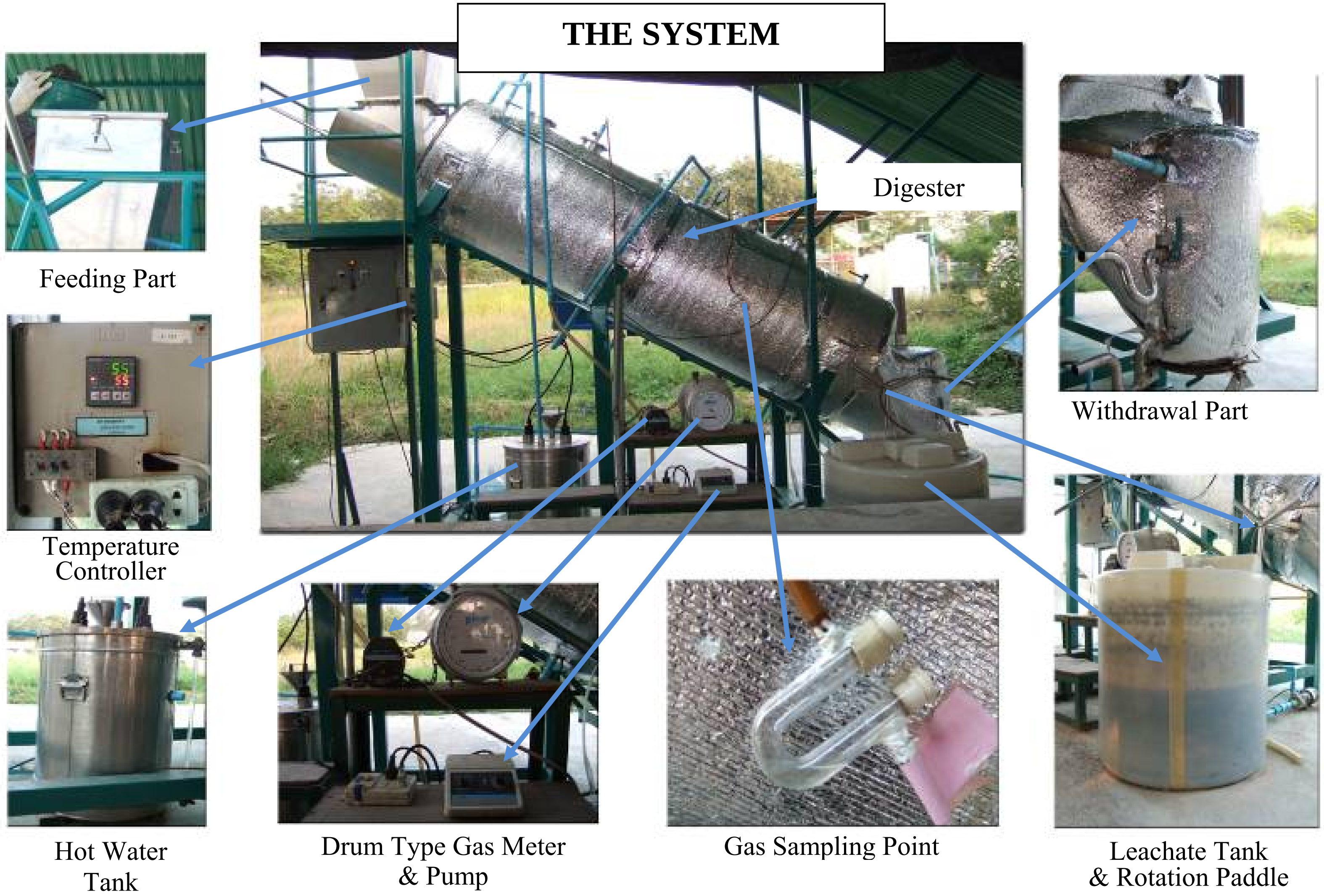
Appendices

Appendix A Photographs

Feed Stock Preparation



Anaerobic Digestion System



Lab-Scale reactors BMP Test

Reactors

Reactors in oven

Gas removal

Experiment in Progress

Biogas Analysis

Appendix B Specimen calculation

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

Weight of sample before drying =1000 g
Weight of sample after drying = 120 g

$$\% \text{ MC} = \frac{1000 - 120}{1000} \text{ x } 100 = 88\%$$

$$\% \text{ TS} = 100 - 88 = 12\%$$

Weight of sample after 105°C = 1.887 g
Weight of sample after 550°C = 0.333 g

$$\% \text{ VS} = \frac{1.887 - 0.333}{1.887} \text{ x } 100 = 82.32\%$$

Total WW of sample = 1159 kg

Dry weight = $(WW \times \%TS) = 1159kg \times 0.12 = 139.08$ kg

Volatile weight = $(Dry\ weight \times \%VS) = 139.08\ kg \times 0.8232 = 114.49$ kg

2. Calculation of methane potential 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 CH_4 (g) = Area (CH_4 peak in chromatograph) * K
K = Constant = $1.7759 * 10^{-10}$
Area_{49} (before removal) = 298008 (49: Run time in days-OFMSW)
Area_{49} (after removal) = 254481

Mass of CH_4 in sample:
m (sample) = $298008 * 1.7759 * 10^{-10} = 52.923$ µg (before removal)
m (sample) = $254481 * 1.7759 * 10^{-10} = 45.193$ µg (after removal)

Step 2: Determination of CH_4 mass in reactor (before and after removal)

Volume of head space in the reactor 2206 mL
Mass of CH_4 in the reactor:

$$M_{49} \text{ (reactor)} = \frac{V}{0.2} * \text{m (sample)}_{49}$$

$$M_{49} \text{ (reactor, before removal)} = \frac{V}{0.2} * \text{m (sample)}_{49}$$

$$= \frac{2206}{0.2} * 52.923 \text{ µg}$$

$$= 0.584\text{g}$$

$$M_{49}\text{ (reactor, after removal)} = \frac{V}{0.2} * \text{m (sample)}_{49}$$

$$= \frac{2206}{0.2} * 45.193\ \mu\text{g}$$

$$= 0.498\text{g}$$

Step 3: Determination of amount of removal

M_i (removal) = m_i (before removal) – m_i (after removal)
M_{49} (removal) = 0.584 – 0.498
= 0.086 g

Step 4: Determination of cumulative gas production (g)

Cumulative mass production = 1.533 + (0.498 + 0.086) = 2.117 g

Step 5: Determination of gas production (L in STP)

Universal gas equation : $PV = \frac{m}{M} * RT$

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

$$V_{49} = \frac{m}{MP} * RT = \frac{2.117}{16*1}(8.205*10^{-2})*298 = 3235.463\ \text{(NmL)}$$

4. Calculation of methane potential

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

5. Energy consumption and production

5. 1. Energy used

5.1.1. Waste shredding

0.48 L of gasoline was consumed by the cutting machine to shred 100 kg of feedstock to approximately 10 mm sized particle (as observed), Energy used to shred 296 kg of waste = 296 * 0.0048 L/kg = 1.42 L

Since, 1 gallon of gasoline = 110, 250 BTU
(Source: http://www.superiorenergysystems.com/property.htm)

110, 250 BTU (1.0551) = 116, 324.8 KJ/gal   1.0551: conversion factor
116, 324.8 KJ/gal (1gal/3.785L) (1.42 L)
43,641KJ = 43.641 MJ

5.1.2 Heating requirements

Because anaerobic reactor is self heating systems and can keep itself at 29°C without significant additional heat input. The energy consumed for heating water from 29°C to 55°C is:

Basis: Entire heating operation
$H = m.\ \rho.\ T$---(Himmelblau, 1996)

Total amount of water heated is estimated to be 43.5L (during 29 days of operation),

$H = 43.5 \times 10^3$ g (1 cal/g °C) (55°C - 29°C)
H = 1,131 Kcal
H = 1,131 Kcal (4.18 KJ/Kcal) = 4,727.58 KJ= 4.72 MJ

E (used) = E (pretreatment) + E (heating)
= 43.641 + 4.72 = 48.361 MJ

5.2 Energy produced

Total volume gas produced: 6.915 m^3

Calorific value of the gas   5000 Kcal/m^3 -----------------------------((Kulkarni, 2003)
5000*6.915 = 34,575 Kcal (4.18 KJ/Kcal) = 144,523.5 KJ
= 144.52 MJ

5.3 Net Energy gained

E (gained) = E (produced) – E (used)
= (144.52 - 48.36) MJ
= 96.16 MJ
= 3.28 MJ/kg VS

6. Example of mass balance

Characteristics of Input Feedstock

Total feedstock wet weight = 12.5 kg
Moisture content = 100 -9 = 91%
Total moisture in a given weight of waste = $0.91 \times 12.5 = 11.375kg$
Total dry solid present in the waste (TS) = $(1 - 0.91) \times 12.5 = 1.125kg$

Volatile solid present in waste (VS) = 1.125 × 0.8367 = **0.94 kg**

Characteristics Withdrawn Feedstock

Volatile solid in leachate = 12 g/L
Total Solid in Leachate = 29 g/L
Moisture content of digestate = 74%
Total solid in digestate = 26%
Volatile solid in digestate = 40.95% TS
Total digestate to be withdrawn (kg) = Y
Total leachate to be withdrawn (L)

Water Mass Balance

Total liquid intake = Total liquid out

$11.375 = (0.74Y) + 0.971L$ -------------------Eq. (1)

Solid Mass Balance

Volaitle solid loss in leachate 12/1000 × L
With daily biogas production of 330 L (50% CH_4 and 50% CO_2), volatile solid loss (if 100% VS) in biogas production (kg) is calculated using:

$\{350 \times [16 \times (50/100) + 44 \times (50/100)] / 22.413\} = 0.441$kg

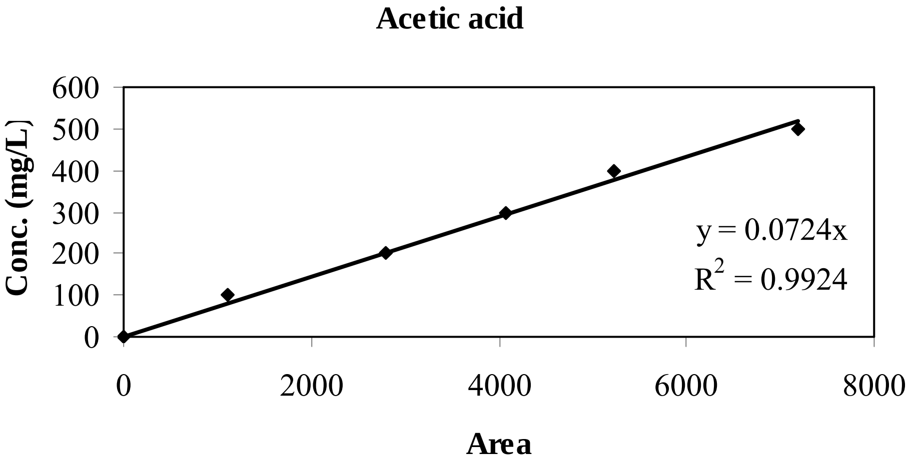
Volatile solid intake = Volatile solid out

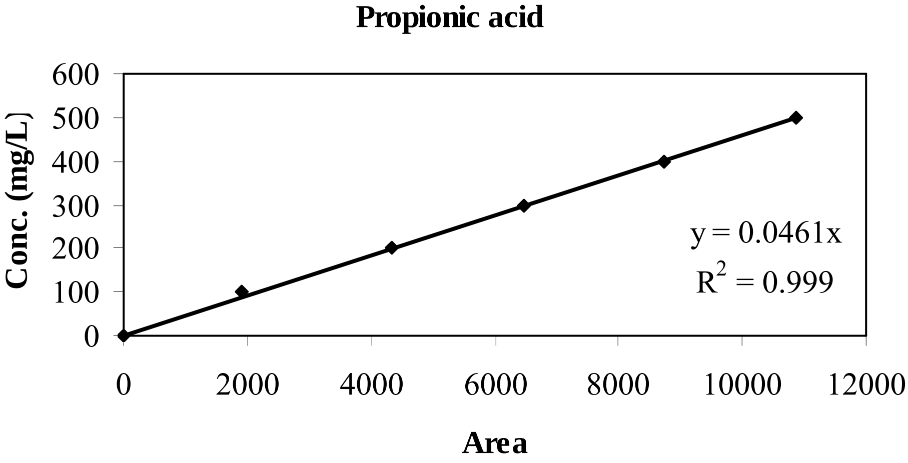
$0.94 = 12/1000 \times L + (0.26 \times 0.4095)Y + 0.441$ ----------------- Eq. (2)

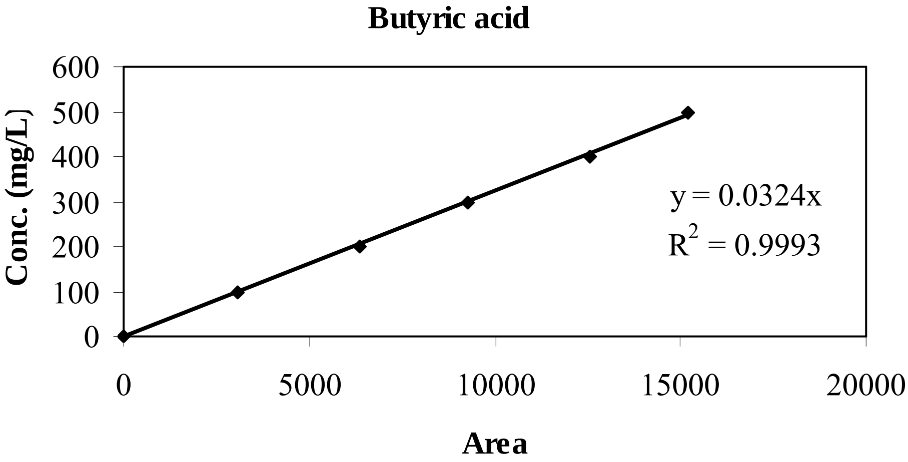
So Y = **3.68 kg**
L = **8.91 L**

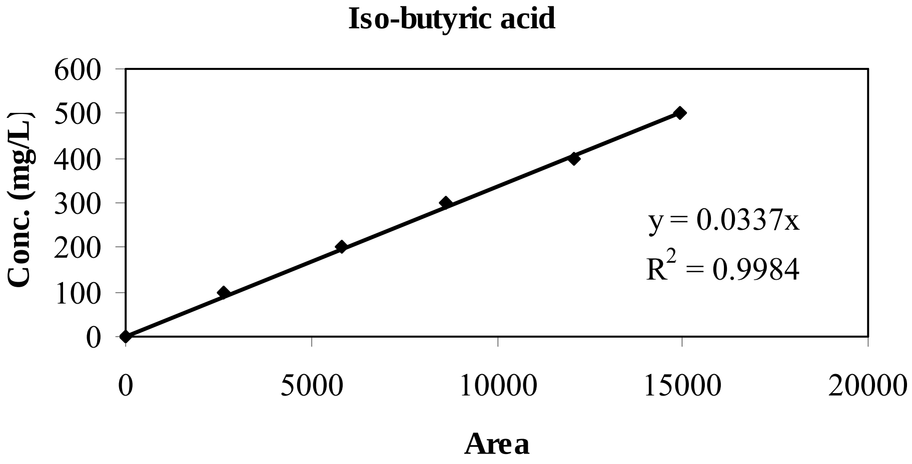
Appendix C Standard Curves

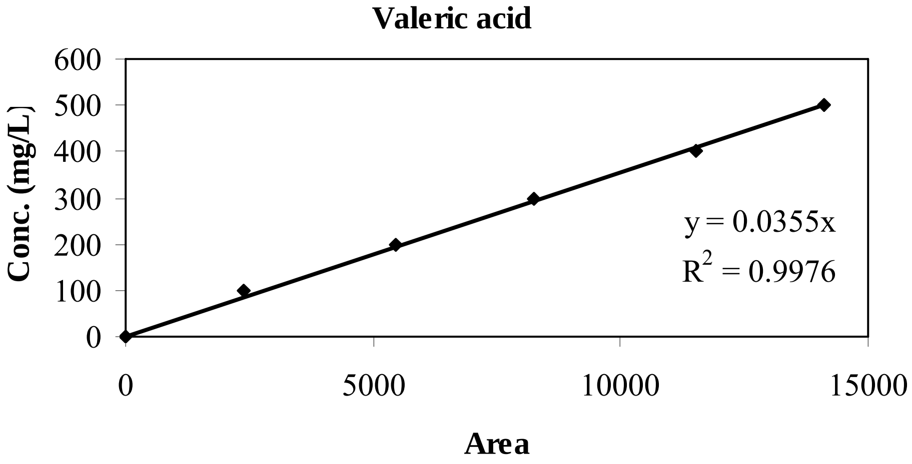
Appendix C-1 Family of VFA Standard Curves





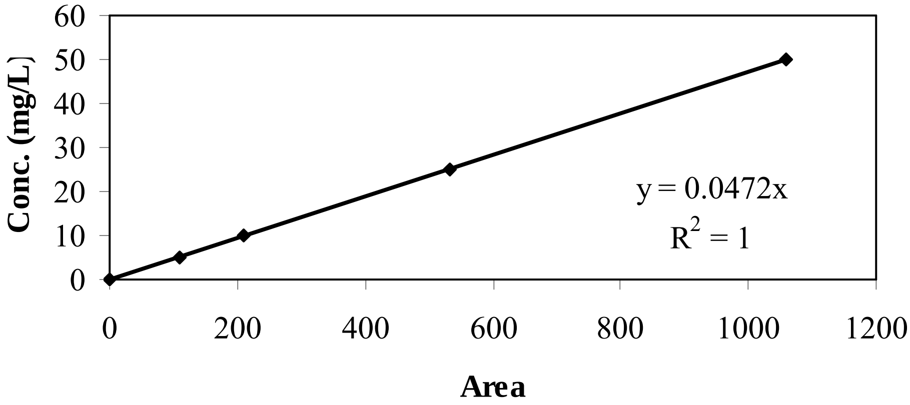



Iso-butyric acid
Conc. (mg/L)
0
100
200
300
400
500
600
0
5000
10000
15000
20000
Area
y = 0.0337x
R2 = 0.9984

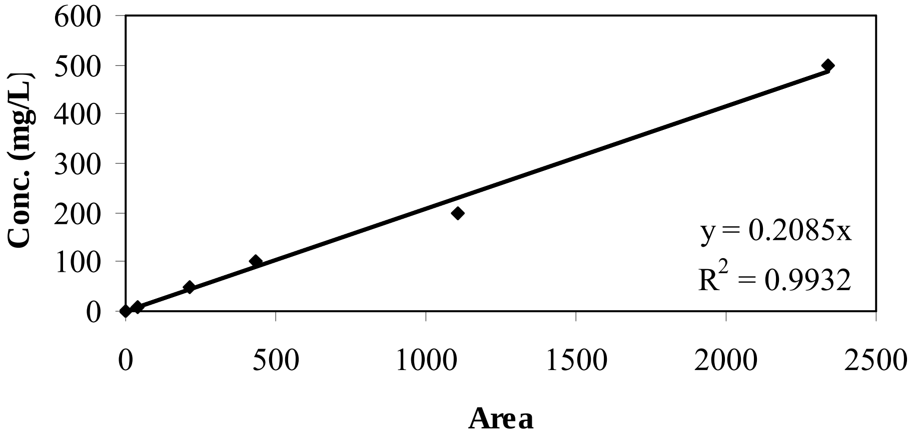

Valeric acid
Conc. (mg/L)
0
100
200
300
400
500
600
0
5000
10000
15000
Area
y = 0.0355x
R2 = 0.9976

Appendix C-2 TC and IC Standards Curves

IC Standard curve



TC Standard curve



Appendix D Pilot Scale-Continuous Anaerobic Digestion

Table D-1 Leachate characteristic during start-up

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	SCOD (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)	SO_4^{2-} (mg/L)	S^{2-} (mg/L)	Remarks
0	6.38	5,250	4,623	7,355	25,000	26,000	1,092	1,568	5,049.15	80	Start up
1	6.81	5,475	4,656	7,945			996.8	1,484			
2	6.03	6,800	5,219	10,065			1,220.8	1,478.4			
3	5.71	6,920	6,129	11,290			1,327.2	1,652			
4	6.38	8,720	4,835	11,620	29,000	37,000	1,484	1,621.2	3,562.65	200	
5	6.44	8,900	4,802	11,780			1,327.2	1,666			
6	6.90	10,060	5,003	12,535			1,327.2	1,635.2			
7	6.86	9,900	1,981	12,535			1,349.6	1,663.2			
8	6.91	10,020	2,132	12,762.5	32,000	42,000	1,377.6	1,638	4,108.15	240	
9	6.80	10,100	2,133	13,100			1,372	1,680			
10	6.97	11,160	1,620	12,807.5			1,356	1,624			
11	6.81	10,360	1,183	13,267.5			1,386	1,782.41			
12	6.96	10,360	2,071	12,399.85	30,000	45,000	1,386	1,676.66	6,824.15	160	
13	7.15	10,520	2,356	12,182.35			1,372	1,733.91			
14	7.22	11,300	2,447	11,334.85			1,380.4	1,631.16			
15	7.34	11,700	2,706	11,234.85			1,458.8	1,849.66			
16	7.43	12,080	1,017	11,174.85	28,000	32,000	1,456	1,879.66	4,270.15	240	
17	7.47	12,600	1,132	10,715			1,545.6	1,982.25			
18	7.61	12,620	1,151	9,767.5			1,509.2	1,758.25			
19	7.53	12,420	1,154	9,082.5			1,299.2	1,766.5			
20	7.61	12,670	1,002	9,165	24,000	30,000	1,542.8	1,872.25	3,981.15	240	

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	SCOD (mg/L)	COD (mg/L)	NH_3-N (mg/L)	TKN (mg/L)	SO_4^{2-} (mg/L)	S^{2-} (mg/L)	Remarks
21	7.67	13,200	1,123	8,377.5			1,512	1,863.5			
22	7.63	12,980	1,008	7,672.5			1,411.2	1,824.25			
23	7.77	12,480	1,248	7,952.5			1,481.2	1,813.75			
24	7.75	12,540	984	7,667.5	19,000	25,000	1,470	1,865.25	3,312.13	360	
25	7.83	13,040	916	7,910			1,556.8	2,033.75			
26	7.79	12,800	931	7,645			1,495.2	2,035.5			
27	7.87	12,960	860	6,766			1,531.6	1,905			
28	7.96	13,100	750	6,484.3	16,000	19,000	1,517.6	1,802.25	3,651.65	320	
29	7.86	13,580	1,027	6,247.3			1,568	1,812.25			

Table D-2 Leachate characteristic during continuous feeding

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	NH_3-N (mg/L)	TKN (mg/L)	Remarks
30	7.18	12,500	1,247	7,067.3	1,459	1,881	Loading 1
31	7.13	12,100	1,082	7,102.3	1,543	1,973	
32	7.16	12,480	2,456	7,224.8	1,585	2,010	
33	7.50	12,580	2,372	6,117.5	1,627	1,941	
34	7.38	12,180	2,343	6,570	1,613	1,979	
35	7.53	12,480	2,259	7,230	1,571	2,064	
36	7.81	13,140	2,188	7,605	1,618	2,098	
37	7.78	12,660	2,055	7,767.5	1,613	2,139	
38	7.74	12,040	2,068	7,667.5	1,562	1,934	
39	7.87	12,440	2,096	7,932.5	1,624	2,048	
40	7.90	12,620	2,128	6,382.5	1,714	1,886	
41	7.83	12,620	2,040	6,760	1,720	1,888	
42	7.99	12,740	3,375	5,952.5	1,733	1,839	
43	7.90	12,520	2,312	5,755	1,711	1,817	
44	7.39	11,320	2,634	7777.5	1,840	2,450	
45	7.46	11,080	2,612	7,235	1,868	2,340	
46	7.67	11,420	2,935	7,010	1,865	2,190	
47	7.69	10,920	1,428	6,950	1,898	2,485	
48	7.94	11,200	1,205	5,450	1,809	2,290	
49	7.84	10,800	1,102	5,625	1,792	2,291	
50	7.94	11,200	2,301	5,565	1,921	2,452	
51	7.79	11,240	2,825	5,385	1,938	2,381	
52	7.77	11,000	2,509	6,150	1,921	2,516	
53	7.62	10,720	2,033	6,155	1,957	1,790	
54	7.54	10,660	2,570	5,820	1,957	2,128	
55	7.64	10,000	2,176	6,920	1,896	2,649	
56	7.46	11,080	3,204	6,100	1,868	2,170	
57	7.54	10,480	4,562		1,912	2,099	
58	7.68	9,860	5,587	6,090	1,893	2,100	
59	7.51	9,700	6,143	6,305	1,896	2,069	
60	7.31	9,540	6,993	7,285	1,926	2,377	
61	7.36	9,860	7,322	7,870	1,954	2,460	
62	7.25	9,540	6,717	6,840	1,926	2,074	
63	7.29	9,260	7,101	6,840	1,954	1,989	
64	7.11	9,360	7,184	6,355	1,915	2,147	
65	7.16	9,000	6,226	9,790	1,994	2,384	
66	7.14	8,920	6,102	8,820	2,016	2,155	
67	6.89	8,400	6,364	9,325	1,949	2,149	

Run time (days)	pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L)	DOC (mg/L)	NH_3-N (mg/L)	TKN (mg/L)	Remarks
68	6.86	8,440	6,449	8,958	1,966	2,418	
69	6.89	8,720	6,020	9,338	2,033	2,276	
70	6.67	8,040	4,880	9,878	2,094	2,146	
71	6.67	8,160	5,931	10,438	2,094	2,260	
72	6.87	8,220	6,773	10,098	2,072	2,302	Unfed
73	6.86	8,340	6,522	10,733	2,061	2,473	Unfed
74	6.96	8,220	6,277	9,903	2,022	2,341	Unfed
75	7.13	8,260	4,876	10,878	2,010	2,576	Unfed
76	7.27	8,420	6,370	9,818	2,066	2,291	Unfed
77	7.43	8,920	6,574	9,408	2,094	2,290	Unfed
78	7.59	8,780	5,348	9,458	2,077	2,465	Unfed
79	7.62	9,220	3,082	7,370	2,139	2,488	Unfed
80	7.67	9,380	3,461	9,005	2,072	2,478	Unfed
81	7.77	9,560	4,282	8,135	2,072	2,399	Unfed
82	7.83	10,300	4,016	8,360	2,217	2,599	Unfed
83	7.86	9,280	2,118	7,500	2,128	2,401	Loading 2
84	7.56	9,720	3,402	6,745	2,240	2,269	
85	7.50	9,560	3,521	8,610	2,206	2,633	
86	7.54	9,860	3,918	8,120	2,172	2,513	
87	7.56	9,440	2,672	8,625	2,178	2,623	
88	7.22	8,960	3,937	8,860	2,161	2,509	
89	7.17	9,260	3,653	8,310	2,262	2,381	
90	7.17	8,960	3,394	8,110	2,296	2,300	
91	6.95	8,620	3,680	8,946	2,234	2,497	
92	6.78	8,100	3,753	9,816	2,178	2,525	
93	6.81	7,760	4,856	10,081	2,161	2,497	
94	6.68	7,960	6,555	10,051	2,189	2,553	
95	6.67	8,160	7,030	10,111	2,195	2,558	
96	6.80	8,540	6,468	10,306	2,108	2,408	pH adjustment
97	6.89	8,560	6,308	10,236	2,245	2,655	
98	6.89	8,700	5,697	10,841	2,234	2,645	
99	6.93	9,160	5,029	10,531	2,312	2,698	
100	6.96	9,120	6,377	10,796	2,290	2,685	
101	6.90	9,360	7,394	11,266	2,329	2,678	
102	6.95	9,440	6,428	8,750	2,312	2,598	
103	6.92	9,340	5,736	9,750	2,324	2,511	

Table D-3 Biogas Production and composition during start-up and continuous feeding

Run time	Daily gas Production (L)	Cumulative gas production (L)	Biogas		Remarks
			% CH_4	%CO_2	
0	119.8	119.8	0.00	100.00	Start up
1	231.8	351.6	0.40	99.60	
2	84.4	436.0	0.46	99.54	
3	19.0	455.0			
4	44.3	499.3	4.78	95.22	
5	87.7	587.0			
6	193.0	780.0			
7	110.6	890.6	36.48	63.52	
8	69.6	960.2	39.56	60.44	
9	189.0	1,149.2	43.70	56.30	
10	299.2	1,448.4	47.00	53.00	
11	321.2	1,769.6	51.16	48.84	
12	412.9	2,182.5	52.69	47.31	
13	429.2	2,611.7	54.97	45.03	
14	445.1	3,056.8	57.02	42.98	
15	458.3	3,515.1	59.80	40.20	
16	473.3	3,988.4	61.22	38.78	
17	494.6	4,483.0	63.92	36.08	
18	480.2	4,963.2	65.11	34.89	
19	520.0	5,483.2	66.44	33.56	
20	504.0	5,987.2	64.57	35.43	
21	449.9	6,437.1	63.65	36.35	
22	356.2	6,793.3	63.65	36.35	
23	298.5	7,091.8	64.39	35.61	
24	291.5	7,383.3	64.03	35.97	
25	268.2	7,651.5	63.90	36.10	
26	241.8	7,893.3	66.10	33.90	
27	173.6	8,066.9	65.35	34.65	
28	149.5	8,216.4	64.37	35.63	
29	147.6	8,364.0			
30	247.0	8,611.0	58.59	41.41	Loading 1 (Daily Feeding)
31	217.5	8,828.5			-
32	190.7	9,019.2	54.38	45.62	-
33	196.3	9,215.5	51.76	48.24	-
34	330.5	9,546.0	39.61	60.39	-
35	337.7	9,883.7	37.28	62.72	-
36	340.2	10,223.9	37.74	62.26	-
37	389.6	10,613.5	37.29	62.71	-
38	386.3	10,999.8	40.90	59.10	-
39	379.2	11,379.0	39.60	60.40	-
40	325.4	11,704.4	50.21	49.79	-
41	364.9	12,069.3	39.66	60.34	-
42	355.2	12,424.5	41.93	58.06	-

Run time	Daily gas Production (L)	Cumulative gas production (L)	Biogas		Remarks
			% CH_4	%CO_2	
43	360.9	12,785.4	37.53	62.47	-
44	237.5	13,022.9	34.02	65.98	(Loading for 2 days
45	323.6	13,346.5	38.68	61.32	-
46	373.4	13,719.9	50.91	49.09	-
47	439.8	14,159.7	51.08	48.92	-
48	309.9	14,469.6	44.08	55.92	-
49	277.7	14,747.3	44.56	55.44	-
50	200.9	14,948.2	44.63	55.37	-
51	169.1	15,117.3	43.09	56.91	-
52	277.6	15,394.9	35.50	64.50	-
53	208.1	15,603.0	39.10	60.90	-
54	250.1	15,853.1	29.33	70.67	-
55	237.3	16,090.4	31.52	68.48	-
56	270.7	16,361.1	31.10	68.90	-
57	220.5	16,581.6	36.28	63.72	-
58	223.0	16,804.6	28.86	71.14	-
59	180.1	16,984.7	31.76	68.24	-
60	240.8	17,225.5	29.55	70.45	-
61	178.6	17,404.1	30.63	69.37	-
62	274.4	17,678.5	29.67	70.33	-
63	197.1	17,875.6	31.30	68.70	-
64	373.1	18,248.7	29.25	70.74	-
65	189.2	18,437.9	31.42	68.58	-
66	299.9	18,737.8			-
67	193.0	18,930.8	30.31	69.69	-
68	218.0	19,148.8			-
69	149.4	19,298.2	27.40	72.60	-
70	350.9	19,649.1			-
71	182.6	19,831.7	28.64	71.36	-
72	174.6	20,006.3	32.54	67.46	Unfed
73	165.2	20,171.5			Unfed
74	149.9	20,321.4	40.09	59.91	Unfed
75	154.6	20,476.0	43.44	56.56	Unfed
76	185.6	20,661.6	47.75	52.25	Unfed
77	196.9	20,858.5	51.55	48.45	Unfed
78	180.9	21,039.4	55.30	44.70	Unfed
79	196.4	21,235.8	57.18	42.82	Unfed
80	188.5	21,424.3	59.90	40.10	Unfed
81	188.7	21,613.0	61.90	38.10	Unfed
82	186.3	21,799.3	64.87	35.13	Unfed
83	213.5	22,012.8	48.05	51.95	Loading 2 (Loading for 4
84	195.9	22,208.7	40.37	59.63	-
85	264.2	22,472.9	38.33	61.67	-
86	216.2	22,689.1	39.00	61.00	-
87	269.2	22,958.3	21.12	78.88	-

Run time	Daily gas Production (L)	Cumulative gas production (L)	Biogas		Remarks
			% CH_4	%CO_2	
88	145.9	23,104.2	21.28	78.72	-
89	121.1	23,225.3	21.29	78.71	-
90	120.5	23,345.8	22.16	77.84	-
91	299.1	23,644.9			(Loading for 10 days)
92	244.1	23,889.0	12.11	87.89	-
93	204.3	24,093.3	14.31	85.69	-
94	213.6	24,306.9	15.17	84.83	-
95	175.5	24,482.4	17.07	82.93	-
96	185.5	24,667.9	20.31	79.69	pH adjustment
97	176.7	24,844.6	25.58	74.42	-
98	89.8	24,934.4	29.39	70.61	-
99	88.7	25,023.1	29.33	70.67	-
100	108.0	25,131.1	28.15	71.85	-
101	110.1	25,241.2	25.78	74.22	-
102	118.0	25,359.2	24.51	75.49	-
103	106.2	25,465.4	24.25	75.75	-

Appendix D-4 Biogas production in STP

Run time (Days)	Volume of gas produced (L/day)	Temperature (°C)	Ambient Pressure Milibar (mb)	Vapor pressure Millibar (mb)	Dry volume of gas (L/day)	Volume of gas (L/day)	Cumulative gas production (L)
0	119.8	29.9	1017.0	32.3	87.50	79.15	79.15
1	231.8	30.1	1017.0	31.3	200.50	181.26	260.41
2	84.4	30.0	1018.5	31.8	52.60	47.64	308.04
3	19.0	30.9	1019.0	28.9	9.90	8.94	299.10
4	44.3	30.5	1018.5	31.7	12.60	11.39	310.49
5	87.7	30.3	1019.0	34.1	53.60	48.52	359.01
6	193.0	28.8	1019.5	31.1	161.90	147.35	506.37
7	110.6	28.8	1022.0	29.1	81.50	74.36	580.73
8	69.6	29.0	1018.0	31.2	38.40	34.88	615.60
9	189.0	28.3	1020.0	28.5	160.50	146.39	761.99
10	299.2	29.9	1020.0	29.3	269.90	244.88	1,006.87
11	321.2	29.7	1019.0	28.2	293.00	265.75	1,272.62
12	412.9	29.0	1021.5	34.8	378.10	344.58	1,617.20
13	429.2	29.3	1022.0	42.1	387.10	352.60	1,969.80
14	445.1	28.8	1019.5	29.3	415.80	378.44	2,348.24
15	458.3	29.1	1019.5	25.5	432.80	393.52	2,741.76
16	473.3	28.5	1020.0	27.8	445.50	406.08	3,147.84
17	494.6	27.6	1021.0	25.3	469.30	429.47	3,577.31
18	480.2	26.9	1020.5	21.7	458.50	420.36	3,997.67
19	520.0	27.3	1024.0	33.2	486.80	447.24	4,444.91
20	504.0	23.9	1025.0	35.8	468.20	435.50	4,880.41
21	449.9	24.7	1024.0	20.8	429.10	397.67	5,278.09
22	356.2	25.1	1024.0	17.4	338.80	313.56	5,591.65
23	298.5	24.8	1024.0	16.8	281.70	260.98	5,852.63
24	291.5	24.1	1024.0	16.2	275.30	255.65	6,108.28
25	268.2	22.3	1022.5	19.8	248.40	231.74	6,340.02
26	241.8	22.1	1022.0	25.2	216.60	202.11	6,542.13
27	173.6	21.6	1021.5	21.5	152.10	142.10	6,684.23
28	149.5	22.8	1021.0	25.5	124.00	115.32	6,799.54
29	147.6	23.8	1020.5	28.7	118.90	110.15	6,909.69
30	247.0	25.3	1021.0	28.3	218.70	201.68	7,111.37
31	217.5	24.8	1021.5	23.6	193.90	179.20	7,290.57
32	190.7	24.3	1023.0	25.5	165.20	153.16	7,443.73
33	196.3	24.3	1022.0	26.9	169.40	156.90	7,600.63
34	330.5	25.5	1022.0	26.5	304.00	280.43	7,881.06
35	337.7	26.5	1021.0	27.7	310.00	284.73	8,165.79
36	340.2	26.1	1020.5	31.0	309.20	284.24	8,450.03

Run time (Days)	Volume of gas produced (L/day)	Temperature (°C)	Ambient Pressure Milibar (mb)	Vapor pressure Millibar (mb)	Dry volume of gas (L/day)	Volume of gas (L/day)	Cumulative gas production (L)
37	389.6	25.9	1019.5	23.8	365.80	336.16	8,786.19
38	386.3	25.9	1019.0	22.2	364.10	334.44	9,120.63
39	379.2	27.5	1019.0	26.4	352.80	322.33	9,442.96
40	325.4	27.3	1022.5	29.6	295.80	271.36	9,714.33
41	364.9	26.6	1021.5	23.4	341.50	313.71	10,028.04
42	355.2	26.4	1023.0	20.4	334.80	308.22	10,336.26
43	360.9	26.8	1023.5	21.3	339.60	312.37	10,648.63
44	237.5	27.0	1023.5	22.2	215.30	197.90	10,846.53
45	323.6	26.6	1022.0	23.8	299.80	275.54	11,122.07
46	373.4	26.8	1021.0	20.9	352.50	323.44	11,445.52
47	439.8	26.3	1021.0	25.3	414.50	380.97	11,826.49
48	309.9	27.0	1021.5	34.5	275.40	252.65	12,079.14
49	277.7	27.1	1020.5	27.9	249.80	228.87	12,308.01
50	200.9	27.3	1019.5	28.0	172.90	158.15	12,466.16
51	169.1	28.4	1020.5	23.5	145.60	132.82	12,598.98
52	277.6	28.5	1020.0	25.9	251.70	229.43	12,828.41
53	208.1	28.3	1020.0	28.3	179.80	164.00	12,992.41
54	250.1	29.5	1020.5	34.5	215.60	195.97	13,188.37
55	237.3	29.3	1021.0	32.7	204.60	186.18	13,374.56
56	270.7	28.1	1021.0	31.5	239.20	218.54	13,593.09
57	220.5	28.6	1023.0	30.3	190.20	173.82	13,766.91
58	223.0	28.6	1023.5	24.8	198.20	181.22	13,948.13
59	180.1	26.9	1023.5	24.1	156.00	143.44	14,091.58
60	240.8	26.3	1023.0	26.6	214.20	197.26	14,288.84
61	178.6	27.0	1025.0	24.2	154.40	142.13	14,430.97
62	274.4	23.6	1027.5	22.4	252.00	235.21	14,666.18
63	197.1	21.8	1027.5	13.4	183.70	172.51	14,838.69
64	373.1	21.9	1026.5	16.9	356.20	334.06	15,172.75
65	189.2	22.6	1026.0	16.2	173.00	161.78	15,334.53
66	299.9	22.5	1026.0	14.8	285.10	266.71	15,601.24
67	193.0	23.2	1027.0	15.4	177.60	165.91	15,767.15
68	218.0	22.6	1026.5	22.5	195.50	182.91	15,950.06
69	149.4	22.7	1024.5	27.4	122.00	113.88	16,063.95
70	350.9	23.5	1022.0	14.2	336.70	312.69	16,376.64
71	182.6	24.5	1022.5	21.7	160.90	149.00	16,525.64
72	174.6	27.1	1023.0	23.8	150.80	138.50	16,664.14
73	165.2	26.1	1023.0	24.2	141.00	129.93	16,794.07
74	149.9	27.5	1023.5	26.1	123.80	113.61	16,907.68
75	154.6	28.5	1022.0	32.6	122.00	111.42	17,019.10

Run time (Days)	Volume of gas produced (L/day)	Temperature (°C)	Ambient Pressure Milibar (mb)	Vapor pressure Millibar (mb)	Dry volume of gas (L/day)	Volume of gas (L/day)	Cumulative gas production (L)
76	185.6	29.0	1022.0	31.4	154.20	140.60	17,159.70
77	196.9	28.8	1021.5	33.0	163.90	149.47	17,309.17
78	180.9	29.8	1021.0	49.0	131.90	119.83	17,428.99
79	196.4	28.5	1022.0	29.2	167.20	152.70	17,581.70
80	188.5	28.8	1021.5	28.8	159.70	145.64	17,727.33
81	188.7	28.8	1025.0	27.4	161.30	147.60	17,874.93
82	186.3	28.8	1019.0	29.4	156.90	142.73	18,017.67
83	213.5	29.0	1019.5	29.8	183.70	167.08	18,184.75
84	195.9	28.8	1018.0	26.7	169.20	153.77	18,338.52
85	264.2	29.8	1018.0	29.0	235.20	213.05	18,551.57
86	216.2	29.7	1018.0	24.0	192.20	174.15	18,725.72
87	269.2	30.4	1017.5	26.7	242.50	219.12	18,944.84
88	145.9	30.3	1017.5	28.0	117.90	106.57	19,051.41
89	121.1	30.8	1019.0	37.8	83.30	75.28	19,126.69
90	120.5	30.0	1019.0	33.2	87.30	79.10	19,205.79
91	299.1	30.9	1017.5	28.3	270.80	244.29	19,450.07
92	244.1	30.2	1017.5	30.5	213.60	193.13	19,643.21
93	204.3	31.0	1017.3	26.5	177.80	160.31	19,803.51
94	213.6	30.0	1017.0	33.4	180.20	162.96	19,966.47
95	175.5	29.3	1019.8	29.5	146.00	132.70	20,099.17
96	185.5	29.0	1020.0	27.4	158.10	143.87	20,243.04
97	176.7	29.0	1020.5	31.6	145.10	132.11	20,375.15
98	89.8	29.8	1020.0	33.9	55.90	50.73	20,425.88
99	88.7	29.8	1020.0	32.9	55.80	50.64	20,476.53
100	108.0	30.1	1019.0	31.2	76.80	69.57	20,546.09
101	110.1	29.7	1018.5	31.3	78.80	71.44	20,617.53
102	118.0	30.6	1020.0	34.3	83.70	75.77	20,693.29
103	106.2	27.6	1019.8	30.3	75.90	69.38	20,762.67

Appendix E Solid waste characteristic of fresh and digested waste

Parameters	Units	Fresh waste	Digestate
Total wet weight	kg	1159	
Moisture Content (MC)	%	88	73
Total Solid (TS)	%	12	27
Total solids (TS)	kg	139.08	
Volatile solids (%VS)	%	82.32	40.95
Total volatile solids (TVS)	kg	114.49	
VS reduction (Loading 1)	%		51
VS reduction (Loading 2)	%		43.22
Heavy metals analysis			
Cr	mg/kg	7.36	13.88
Cd	mg/kg	0.25	0.64
Ni	mg/kg	4.10	12.16
Pb	mg/kg	0	0
Zn	mg/kg	72.24	105.74
Cu	mg/kg	15.19	54.66
Mn	mg/kg	88.10	86
Hg	mg/kg	0.02	0.0345
Nutrients analysis			
N	%	3.04	1.09
P	%	0.22	0.65
K	%	0.22	0.65
C	%	45.73	22.75
C/N		15.04	20.87
Calorific value	MJ/kg		11.15

Appendix F Daily feed stock input and withdrawal (Continuous digestion)

Total wet weight input (kg/day)	Volatile solid (kg)	Total water (kg)	Digestate to be decanted (kg)	Moisture content (%)	Volatile solid in digestate (kg)	Water in digestate (kg)	Volatile solid in leachate (kg/L)	Daily biogas production (L)	Weight of biogas (kg)	Water in Leachate (L)	Leachate to be withdrawn (L)
12.5	0.94	11.375	**4.19**	73	0.46	3.06	0.103	272.9	0.368	8.30	**8.55**
16	1.20	14.56	**7.01**	73	0.78	5.12	0.117	180	0.308	9.44	**9.72**

Appendix G BMP data in Lab-scale

Sample no.	Run time (days)	Chromatographic area of CH_4		Mass of CH4 (ug) in 0.2 mL		Mass of CH_4 per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	Cumulative volume production (L)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
OFMSW											
0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0
1	1	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2	2	2942	2942	0.522	0.522	0.006	0.006	0.000	0.000	0.006	8.805
3	3	41119	41119	7.302	7.302	0.081	0.081	0.000	0.000	0.081	123.085
4	4	166220	166220	29.519	29.519	0.326	0.326	0.000	0.000	0.326	497.566
5	5	243646	243646	43.269	43.269	0.477	0.477	0.000	0.000	0.477	729.335
6	6	282322	282322	50.137	50.137	0.553	0.553	0.000	0.000	0.553	845.109
7	7	314574	199255	55.865	35.386	0.616	0.390	0.226	0.226	0.842	1286.852
8	9	336612	218329	59.779	38.773	0.659	0.428	0.232	0.458	1.117	1706.893
9	11	313342	224121	55.646	39.802	0.614	0.439	0.175	0.632	1.246	1904.313
10	13	283582	213781	50.361	37.965	0.555	0.419	0.137	0.769	1.325	2024.173
11	15	279670	224782	49.666	39.919	0.548	0.440	0.108	0.877	1.424	2176.766
12	17	260205	214293	46.210	38.056	0.510	0.420	0.090	0.967	1.476	2255.933
13	19	283283	283283	50.308	50.308	0.555	0.555	0.000	0.967	1.521	2325.015
14	21	311343	311343	55.291	55.291	0.610	0.610	0.000	0.967	1.576	2409.011
15	23	388645	388645	69.019	69.019	0.761	0.761	0.000	0.967	1.728	2640.409
16	25	385177	301307	68.403	53.509	0.754	0.590	0.164	1.131	1.885	2881.086
17	29	383978	383978	68.191	68.191	0.752	0.752	0.000	1.131	1.883	2877.497
18	33	384743	292863	68.326	52.009	0.754	0.574	0.180	1.311	2.064	3154.823
19	37	369628	369628	65.642	65.642	0.724	0.724	0.000	1.311	2.035	3109.578

Sample no.	Run time (days)	Chromatographic area of CH_4		Mass of CH4 (ug) in 0.2 mL		Mass of CH_4 per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	Cumulative volume production (L)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
20	41	369742	344437	65.662	61.168	0.724	0.675	0.050	1.360	2.085	3185.668
21	45	339780	294938	60.341	52.378	0.666	0.578	0.088	1.448	2.114	3230.210
22	49	298008	254481	52.923	45.193	0.584	0.498	0.085	1.533	2.117	3235.463
23	50	308800	308800	54.840	54.840	0.605	0.605	0.000	1.533	2.138	3267.769
Blank											
0	0	0	0	0	0	0.000	0.000	0	0	0	0
1	1	0	0	0.000	0.000	0.000	0.000	0	0	0.000	0.002
2	2	1447	1447	0.257	0.257	0.003	0.003	0	0	0.003	4.330
3	3	3151	3151	0.559	0.559	0.006	0.006	0	0	0.006	9.431
4	4	6421	6421	1.140	1.140	0.013	0.013	0	0	0.013	19.219
5	5	12671	12671	2.250	2.250	0.025	0.025	0.000	0.000	0.025	37.928
6	6	24051	24051	4.271	4.271	0.047	0.047	0.000	0.000	0.047	71.993
7	7	35509	30478	6.306	5.412	0.070	0.060	0.010	0.010	0.079	121.352
8	9	40356	39558	7.167	7.025	0.079	0.077	0.002	0.011	0.090	138.250
9	11	42311	42311	7.514	7.514	0.083	0.083	0.000	0.011	0.094	144.102
10	13	49304	47884	8.756	8.504	0.097	0.094	0.003	0.014	0.111	169.286
11	15	61038	55782	10.840	9.906	0.120	0.109	0.010	0.024	0.144	220.144
12	17	62441	62441	11.089	11.089	0.122	0.122	0.000	0.024	0.147	224.344
13	19	63505	61975	11.278	11.006	0.124	0.121	0.003	0.027	0.152	232.109
14	21	67355	67355	11.961	11.961	0.132	0.132	0.000	0.027	0.159	243.633
15	23	70046	70046	12.439	12.439	0.137	0.137	0.000	0.027	0.165	251.689
16	25	70323	64926	12.489	11.530	0.138	0.127	0.011	0.038	0.176	268.673
17	29	73841	73841	13.113	13.113	0.145	0.145	0.000	0.038	0.183	279.204

Sample no.	Run time (days)	Chromatographic area of CH_4		Mass of CH4 (ug) in 0.2 mL		Mass of CH_4 per reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass production (g)	Cumulative volume production (L)
		Before removal	After removal	Before removal	After removal	Before removal	After removal				
18	33	75834	75834	13.467	13.467	0.149	0.149	0.000	0.038	0.187	285.170
19	37	78326	78326	13.910	13.910	0.153	0.153	0.000	0.038	0.191	292.630
20	41	84217	84217	14.956	14.956	0.165	0.165	0.000	0.038	0.203	310.264
21	45	84720	84720	15.045	15.045	0.166	0.166	0.000	0.038	0.204	311.770
22	49	85337	85337	15.155	15.155	0.167	0.167	0.000	0.038	0.205	313.617
23	50	83840	83840	14.889	14.889	0.164	0.164	0.000	0.038	0.202	309.136

Anaerobic Digestion of Municipal Solid Waste in Thermophilic Continuous Operation

By

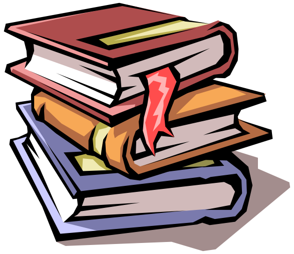
Chea Eliyan

Examination Committee:

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

April 27, 2007

Contents



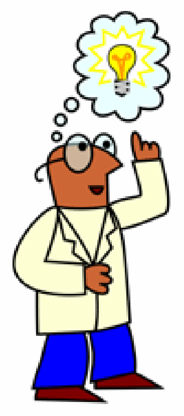
Background

Biomethanization

Agricultural Waste

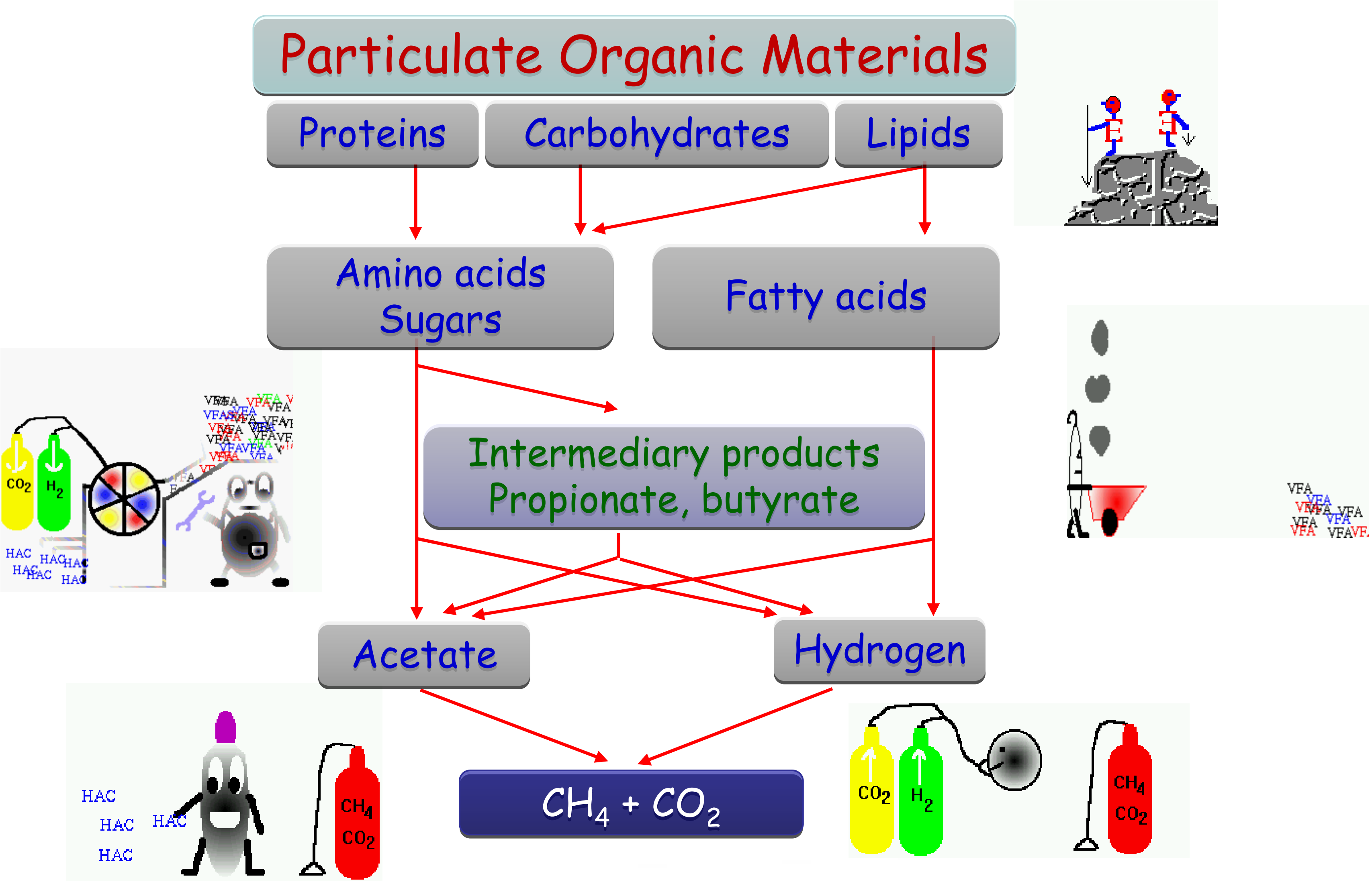
Agro-industrial Waste

Municipal Solid Waste



- Energy generation
- Fertilizer Production
- Environmental protection

Background (Con't)



Particulate Organic Materials

Proteins

Carbohydrates

Lipids

Amino acids
Sugars

Fatty acids

Intermediary products
Propionate, butyrate

Acetate

Hydrogen

$CH_4 + CO_2$

Objectives of the Study

- Develop operational design criteria for the horizontal anaerobic reactor under continuous operation using OFMSW as substrate;
- Evaluate the performance/efficiency of a continuous reactor in continuous mode of operation;
- Investigate the fate of heavy metals during the digestion period using material balance analysis.

Scopes of the Study

- OFMSW was used as a substrate, collected from the Taklong Municipality dumpsite, Pathumthani, Thailand;
- AD of OFMSW experiments was conducted in the continuous mode of operation (pilot scale reactors);
- Maximum temperature of thermophilic (55°C) and using a reduced particle size of 10 mm was used in this study.
- BMP test was conducted in lab scale

Methodology

Pilot Scale Experiment

Horizontal Continuous Anaerobic Digestion

- Reactor starts up (initial feeding to 80% of reactor volume)
- Start at mesophilic condition (increase 2°C/day to thermophilic)

pH adjustment

Variation of loading rates

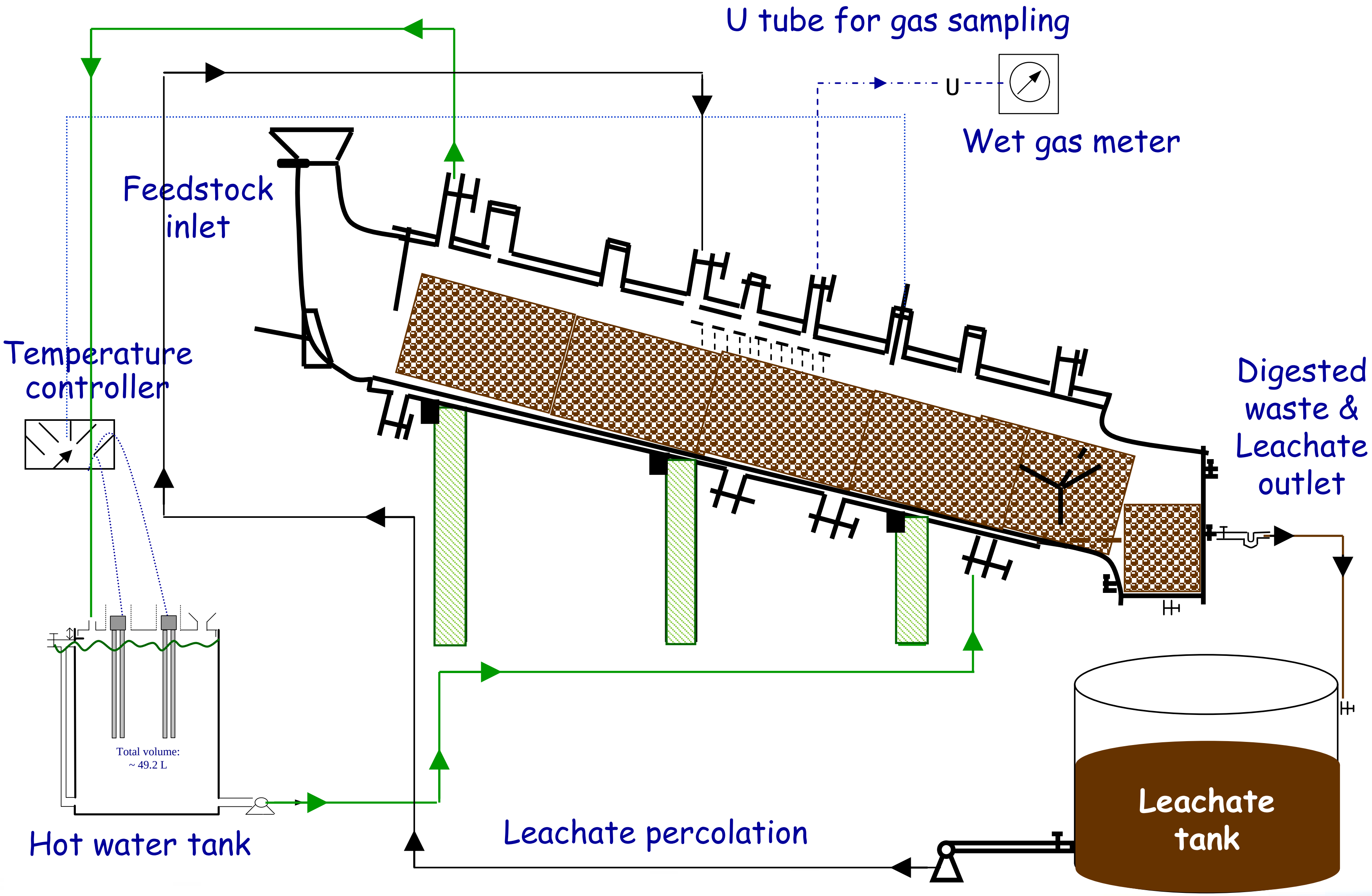
Digested Waste

Laboratory Scale

Biochemical Methane Potential (BMP) Test

Sampling and Analysis

Experimental Sets up



Experimental Sets up (Con’t)

THE SYSTEM

Feeding Part

Digester

Temperature Controller

Withdrawal Part

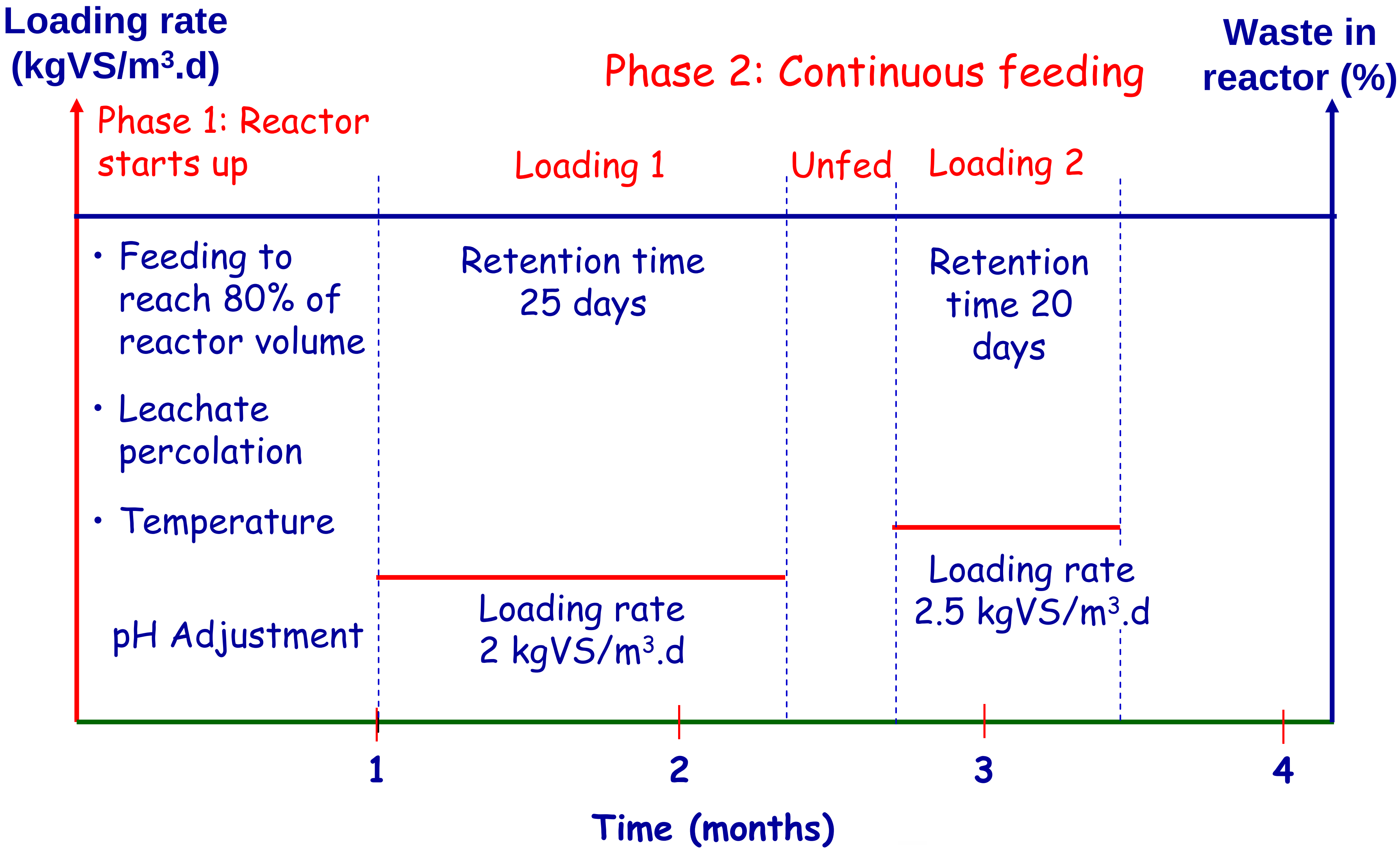
Hot Water Tank

Drum Type Gas Meter & Pump

Gas Sampling Point

Leachate Tank & Rotation Paddle

Pilot Scale Experiment



Phase 1: Reactor starts up

- Feeding to reach 80% of reactor volume
- Leachate percolation
- Temperature

pH Adjustment

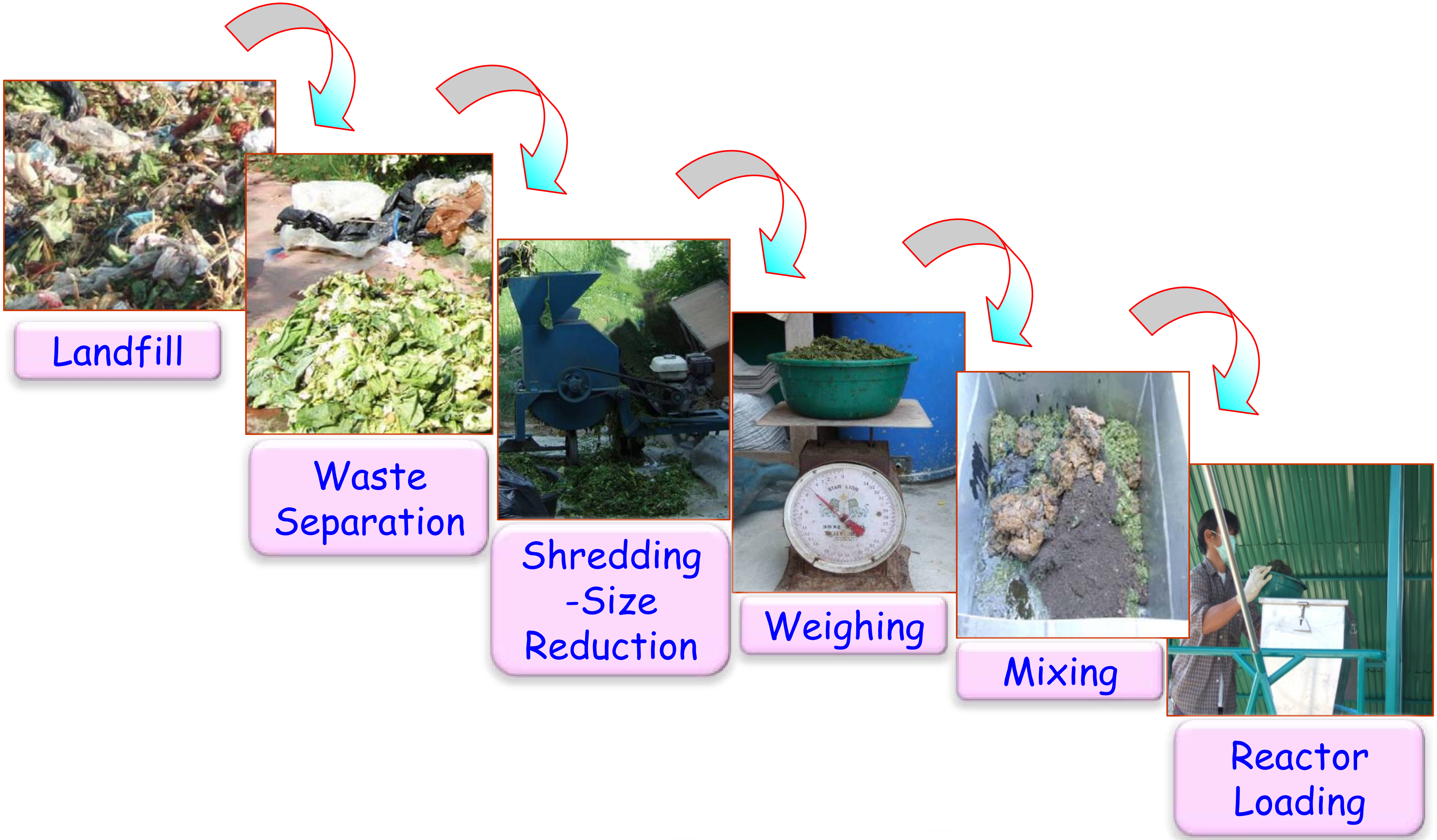
Phase 2: Continuous feeding

Loading 1: Retention time 25 days; Loading rate 2 kgVS/m^3.d

Unfed

Loading 2: Retention time 20 days; Loading rate 2.5 kgVS/m^3.d

Feedstock Preparation



Landfill

Waste Separation

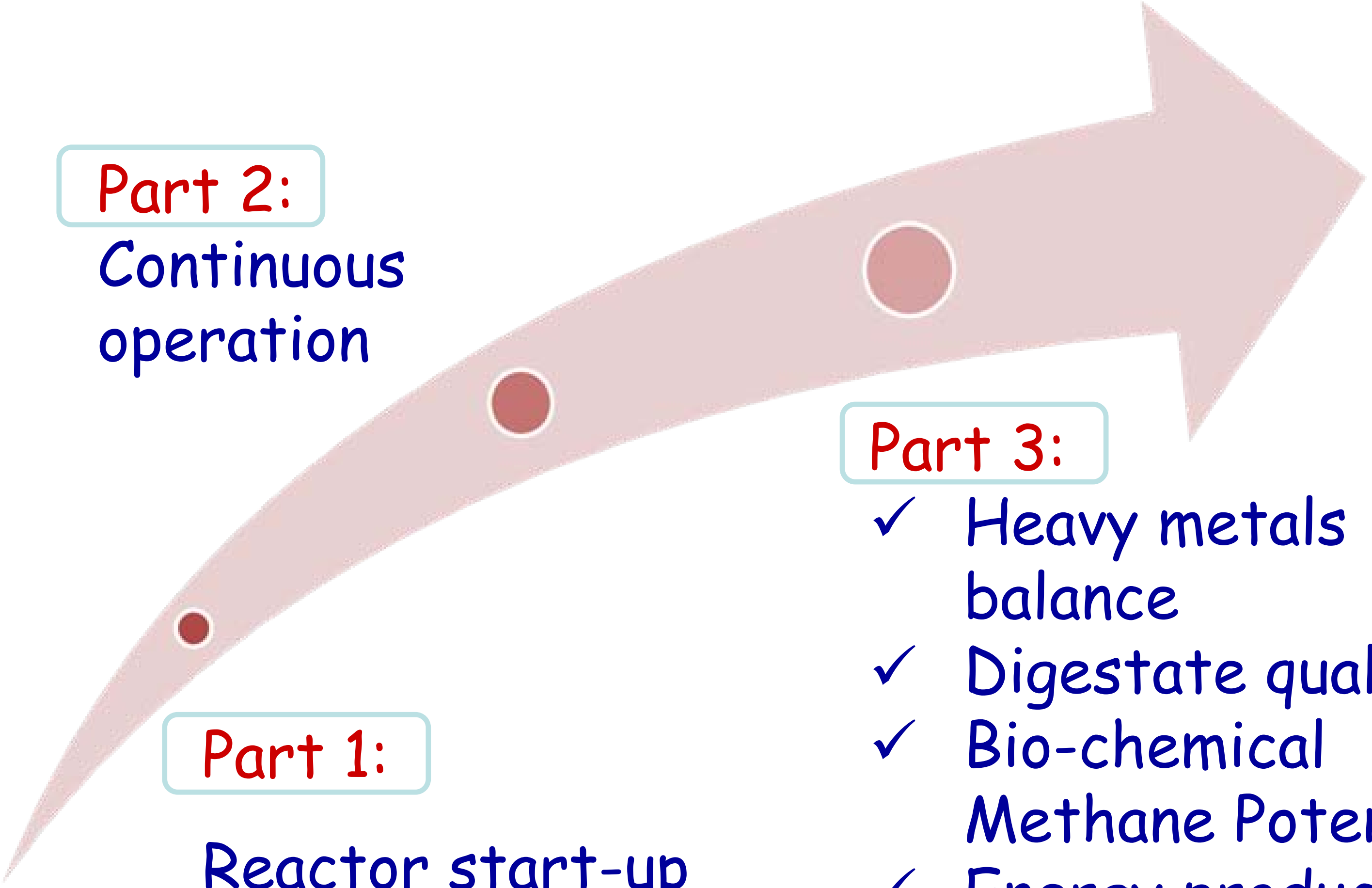
Shredding -Size Reduction

Weighing

Mixing

Reactor Loading

Results and Discussions



Part 2:

Continuous operation

Part 1:

Reactor start-up

Part 3:

- ✓ Heavy metals balance
- ✓ Digestate quality
- ✓ Bio-chemical Methane Potential
- ✓ Energy production and consumption

Feedstock Characteristics

Parameters	OFMSW
MC (%WW)	88-91
TS (%WW)	9-12
VS (%TS)	82.32-83.67
FS (%TS)	17.68-16.33
N (% D.M)	3.04
P (% D.M)	0.22
K (% D.M)	0.22
C (%WW)	45.73
C/N	15.04

High MC and VS

Heavy metals	Conc. (mg/ kg D.M)
Cadmium (Cd)	0.25
Lead (Pb)	0
Zinc (Zn)	72.24
Copper (Cu)	15.29
Chromium (Cr)	7.36
Nickel (Ni)	4.10
Mercury (Hg)	0.036
Manganese (Mn)	88.10

Low concentration of heavy metals

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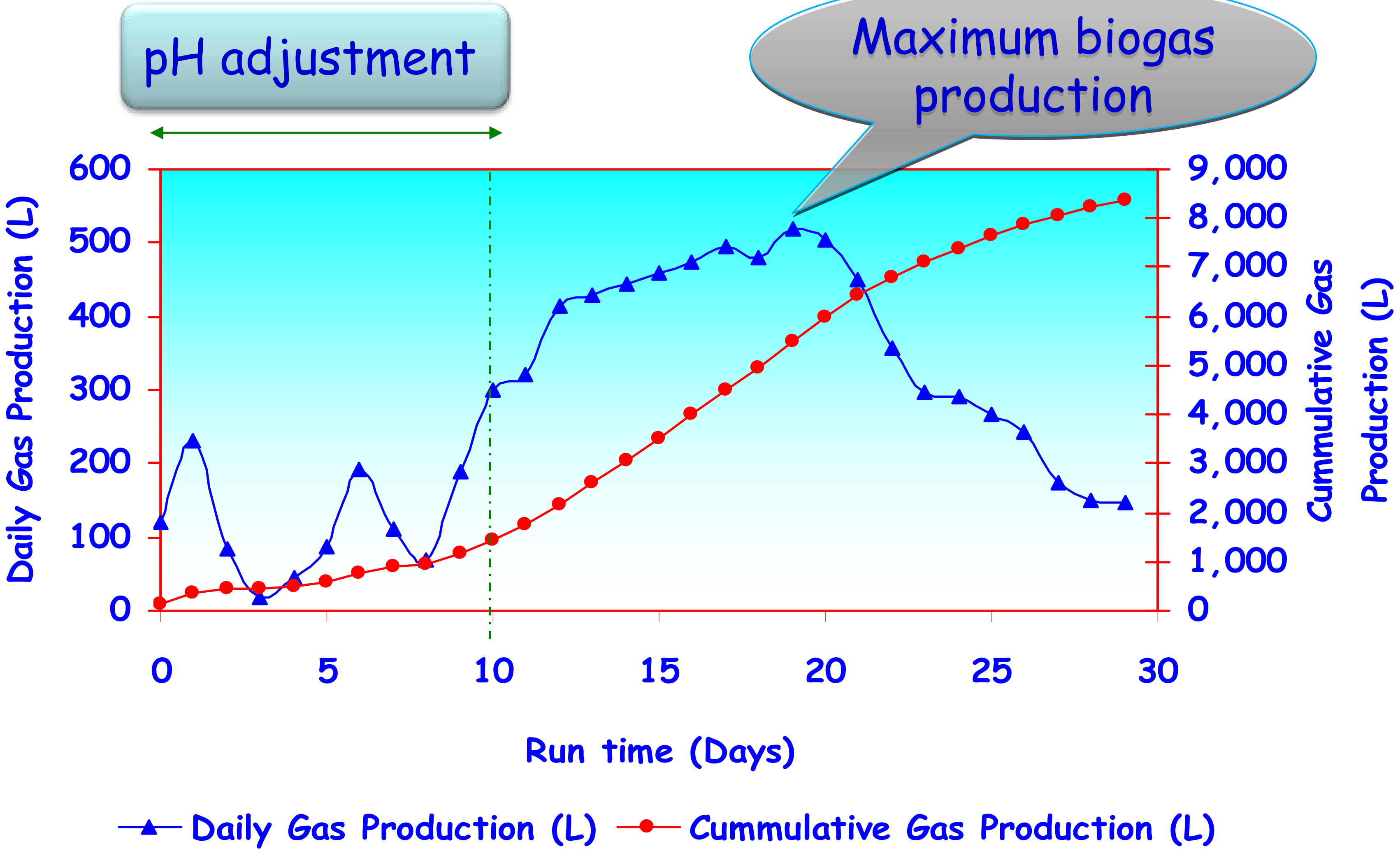
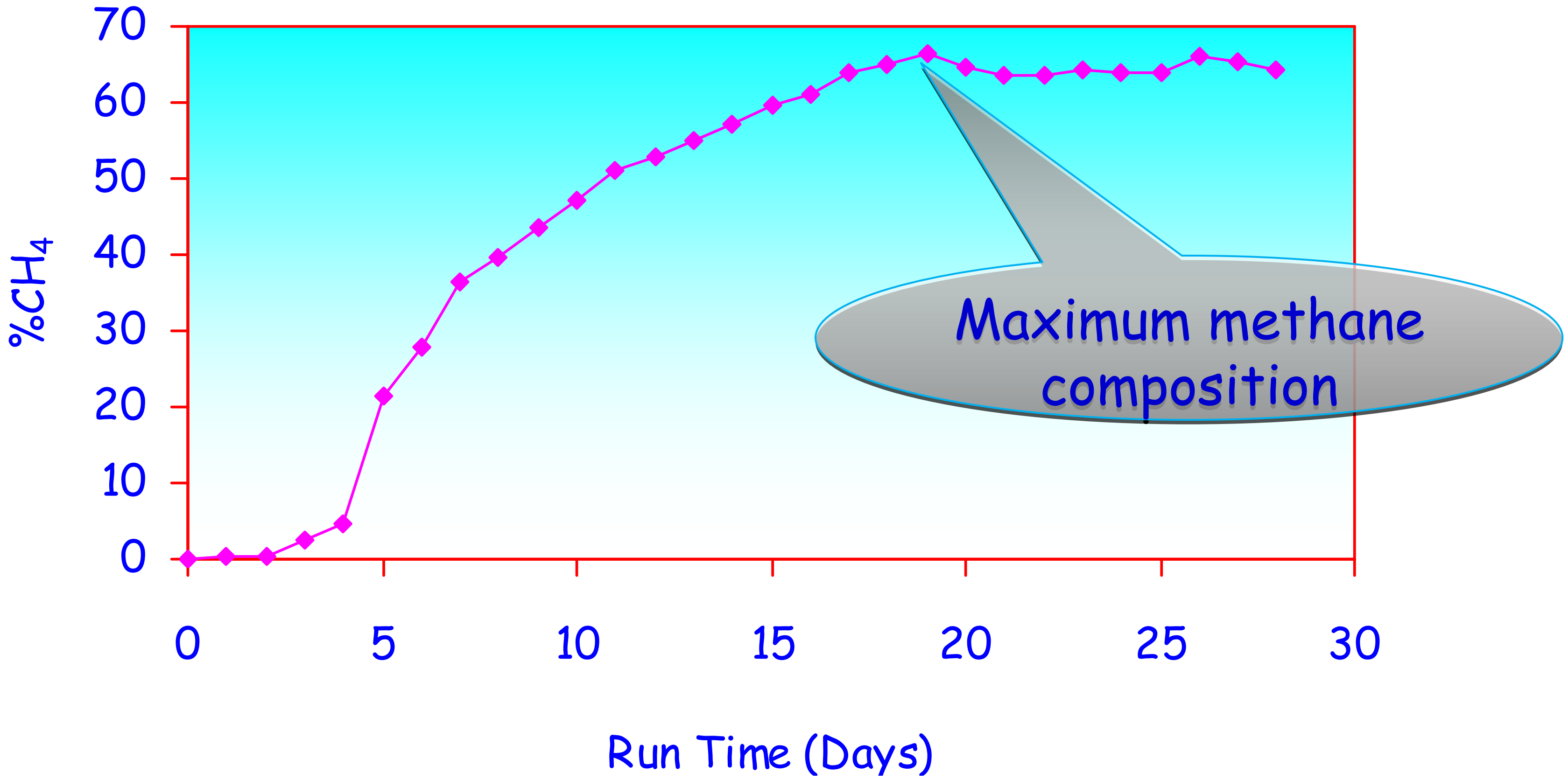
Part 1: Biogas Production

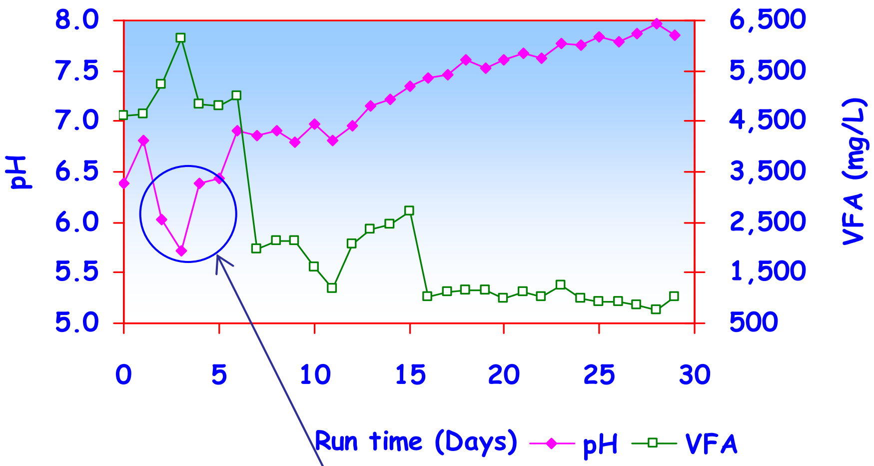


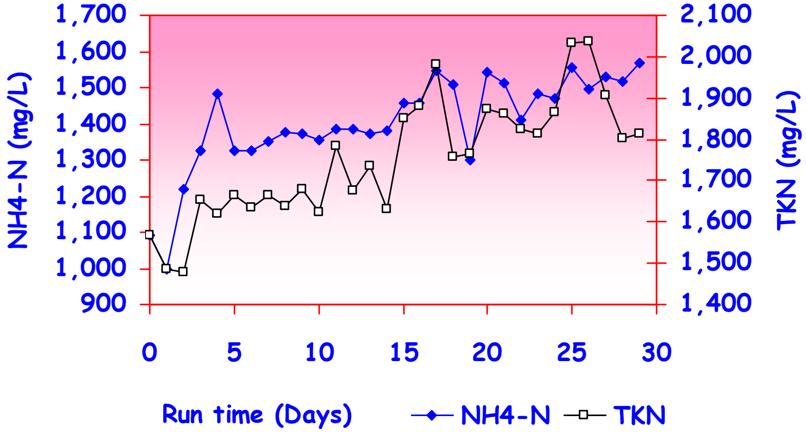
Part 1: Biogas Composition



Steady increase of methane composition was observed & the highest biogas production was also achieved the same day

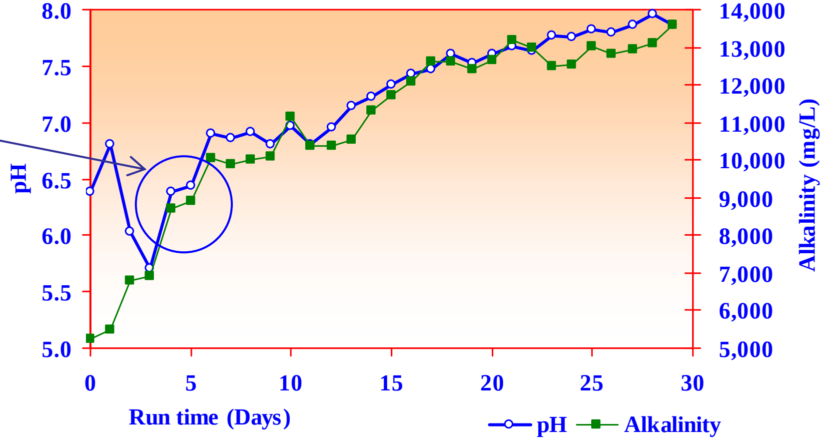
Part 1: Leacahte Characteristics





Ammonia inhibition not occurred.

The steady increased of pH was observed from day 3



⇨ Stable condition of the system

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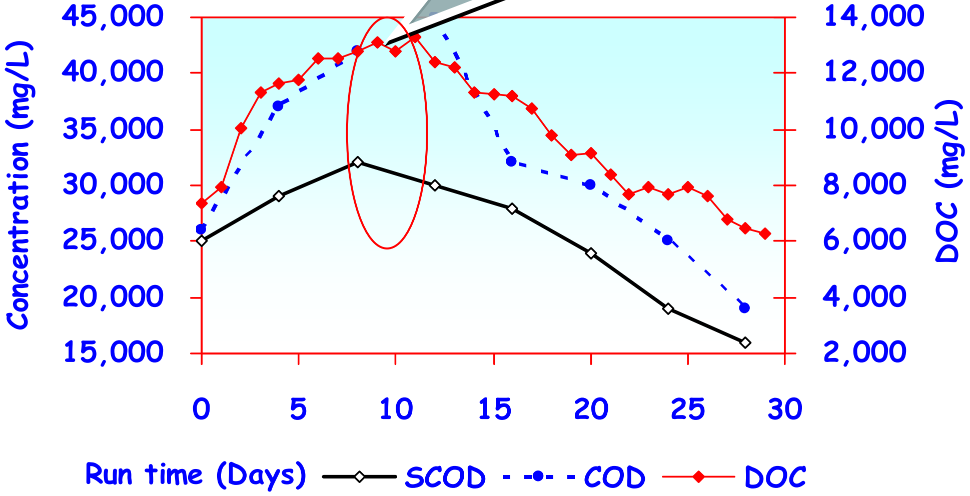
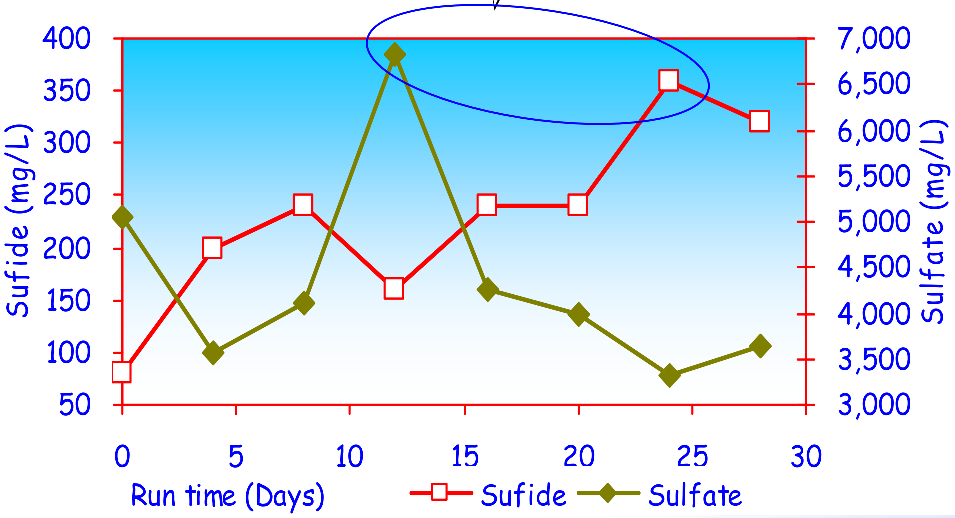
Part 1: Leacahte Characteristics

High hydrolysis rate



Optimum sulfate and sulfide concentration

A parallel increased in COD and DOC concentration



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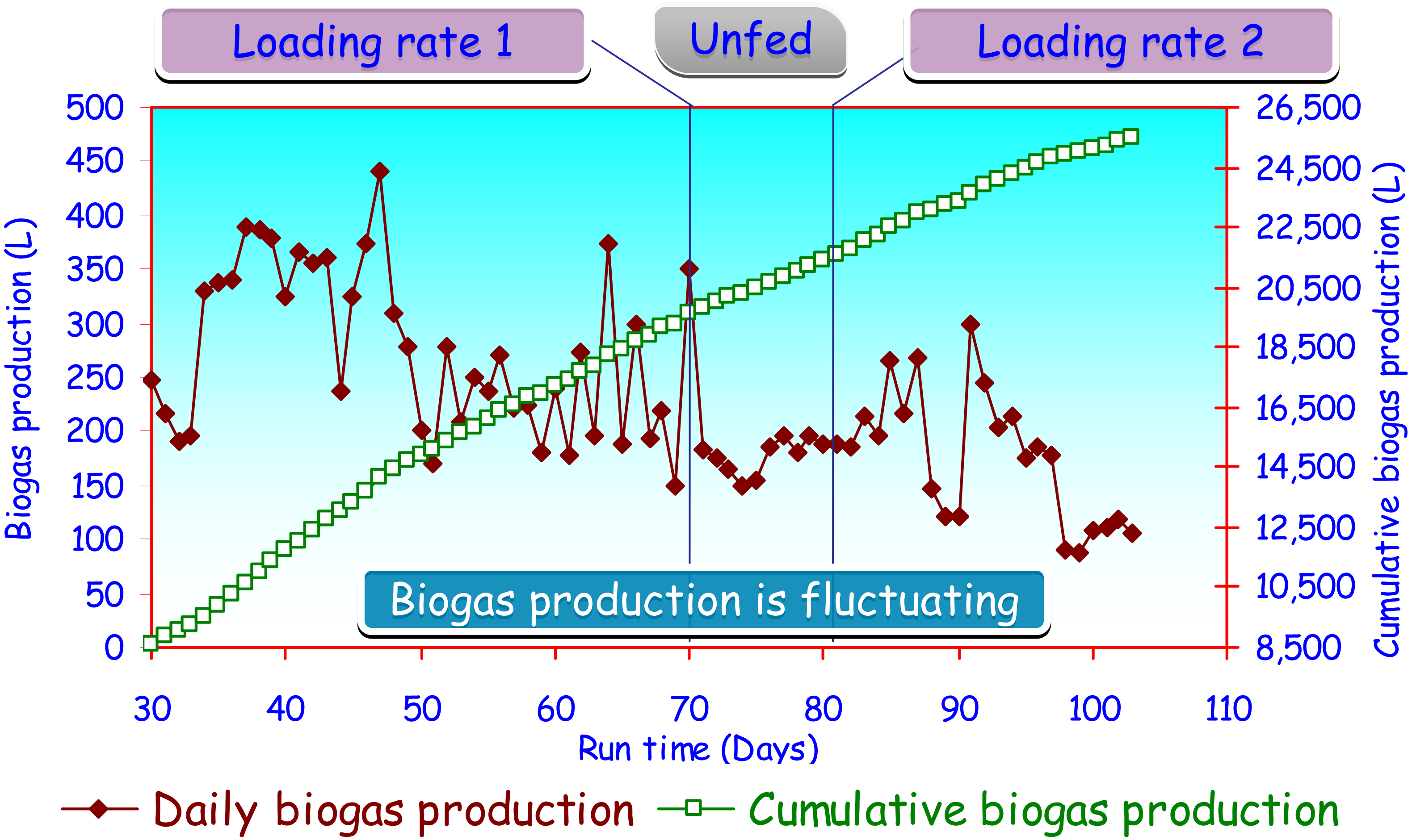
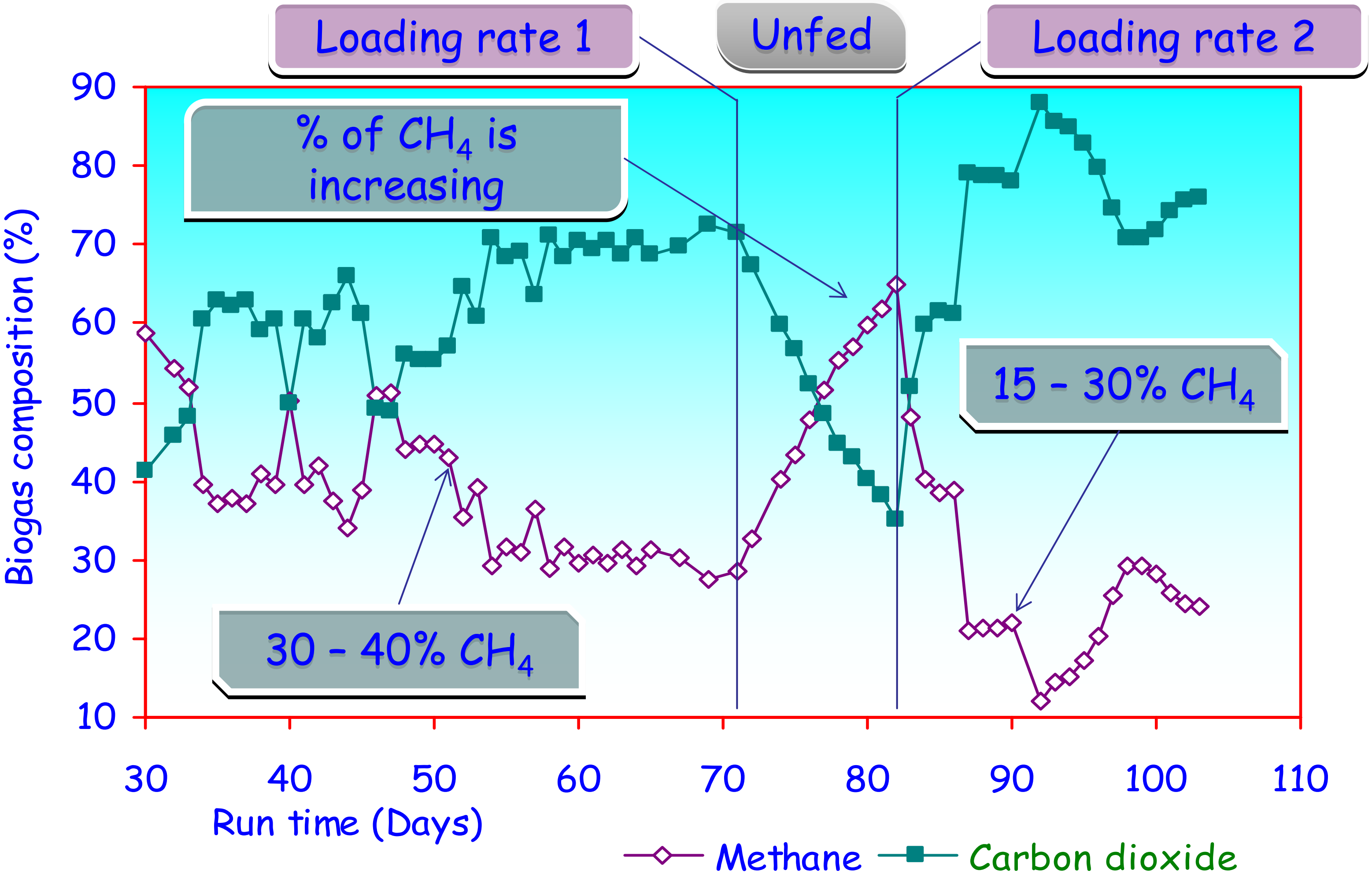
Part 2: Biogas Production



Part 2: Biogas Composition



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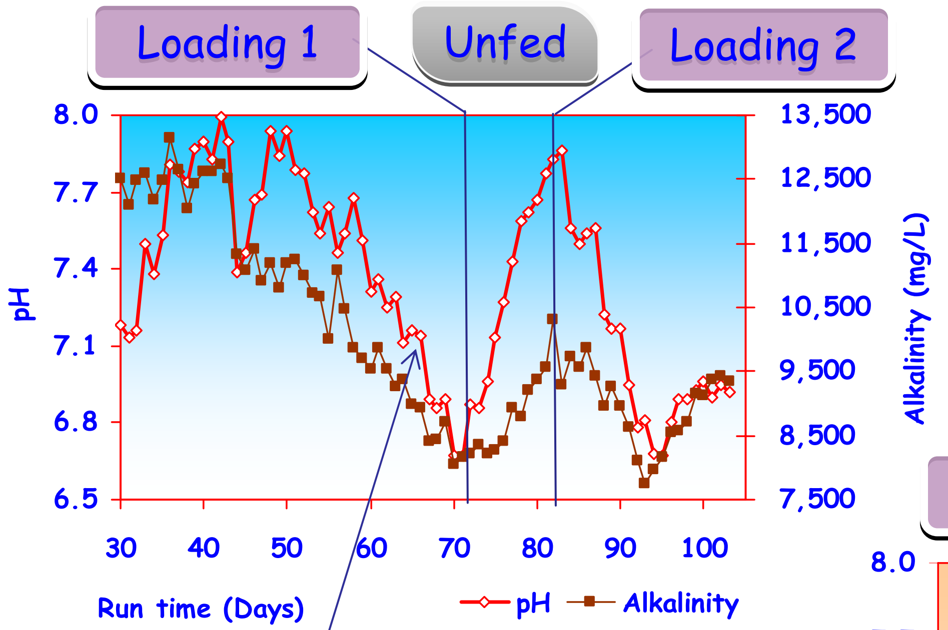
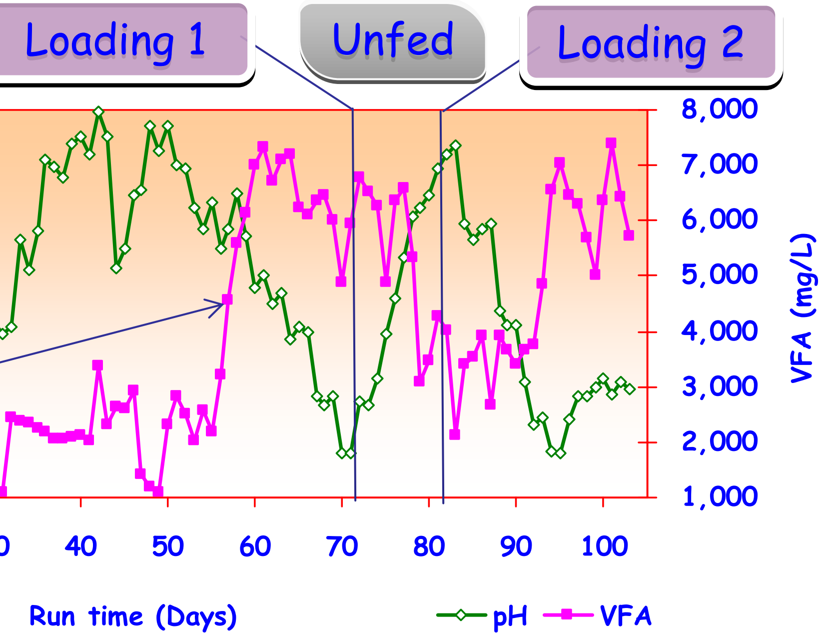
Part 2: Leachate Characteristics



Gradual increase of pH & alkalinity, in Unfed condition

Significant pH dropped



Significant VFA increased

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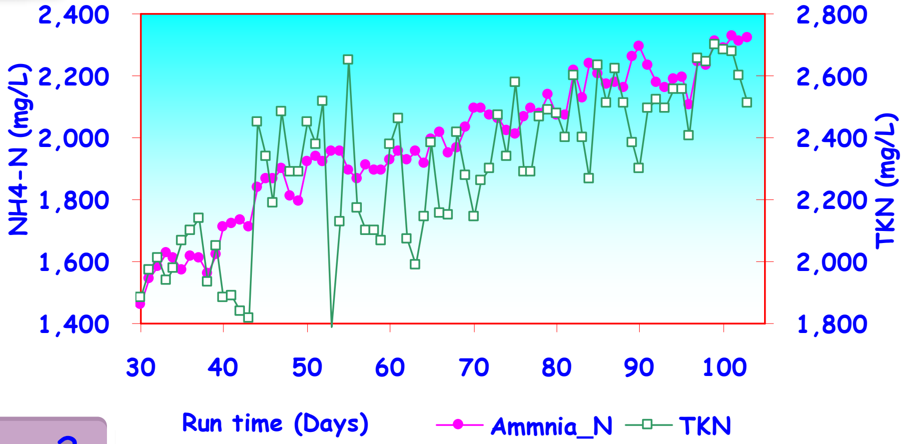
Part 2: Leachate Characteristics

Gradual increased of NH_4-N & TKN when loading rate is increased

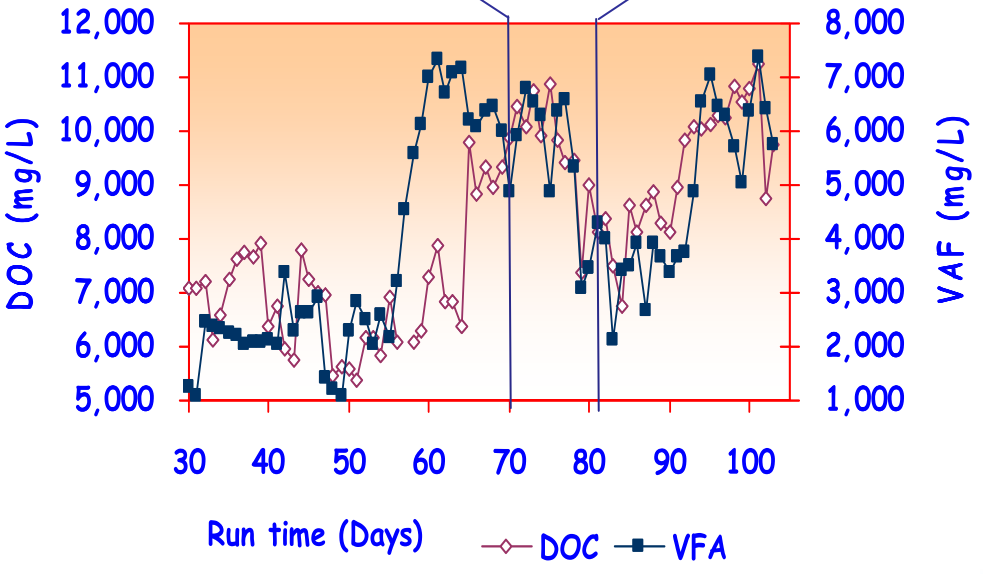


Parallel increased of DOC & VFA was observed

Loading 1

Unfed

Loading 2



➡ Unstable condition of the operating system

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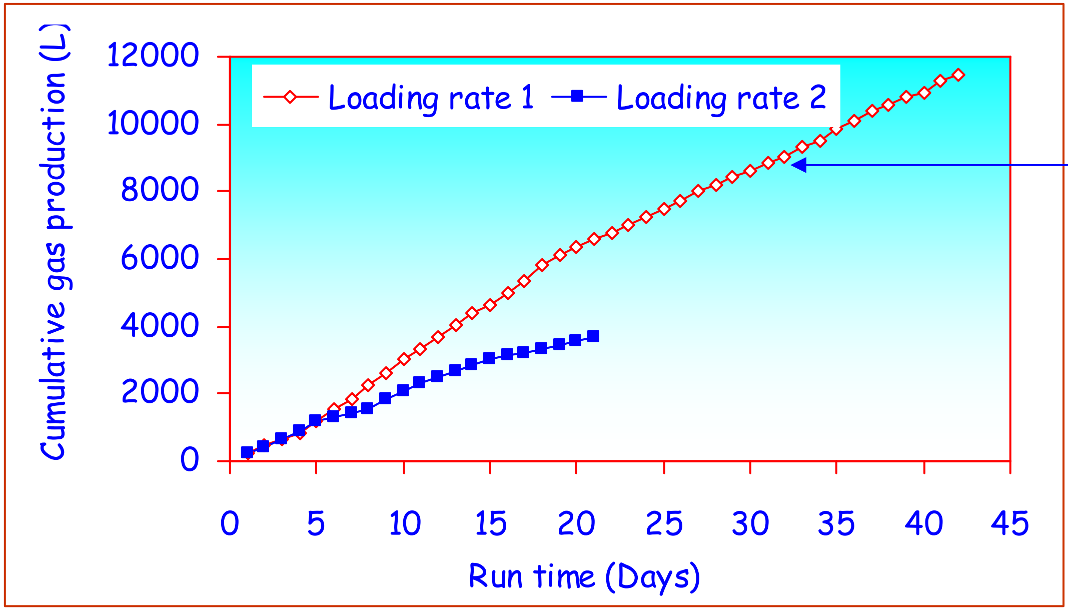
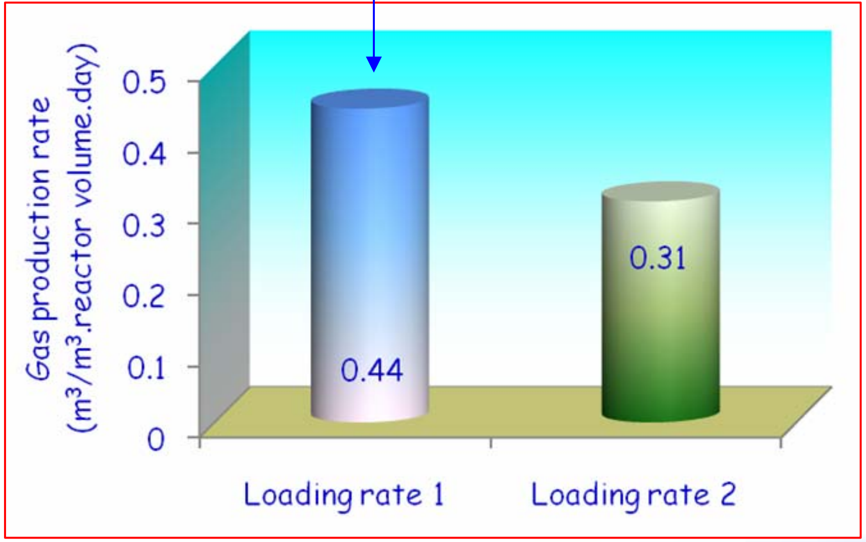
Part 2: Overall Assessment



Higher gas production rate



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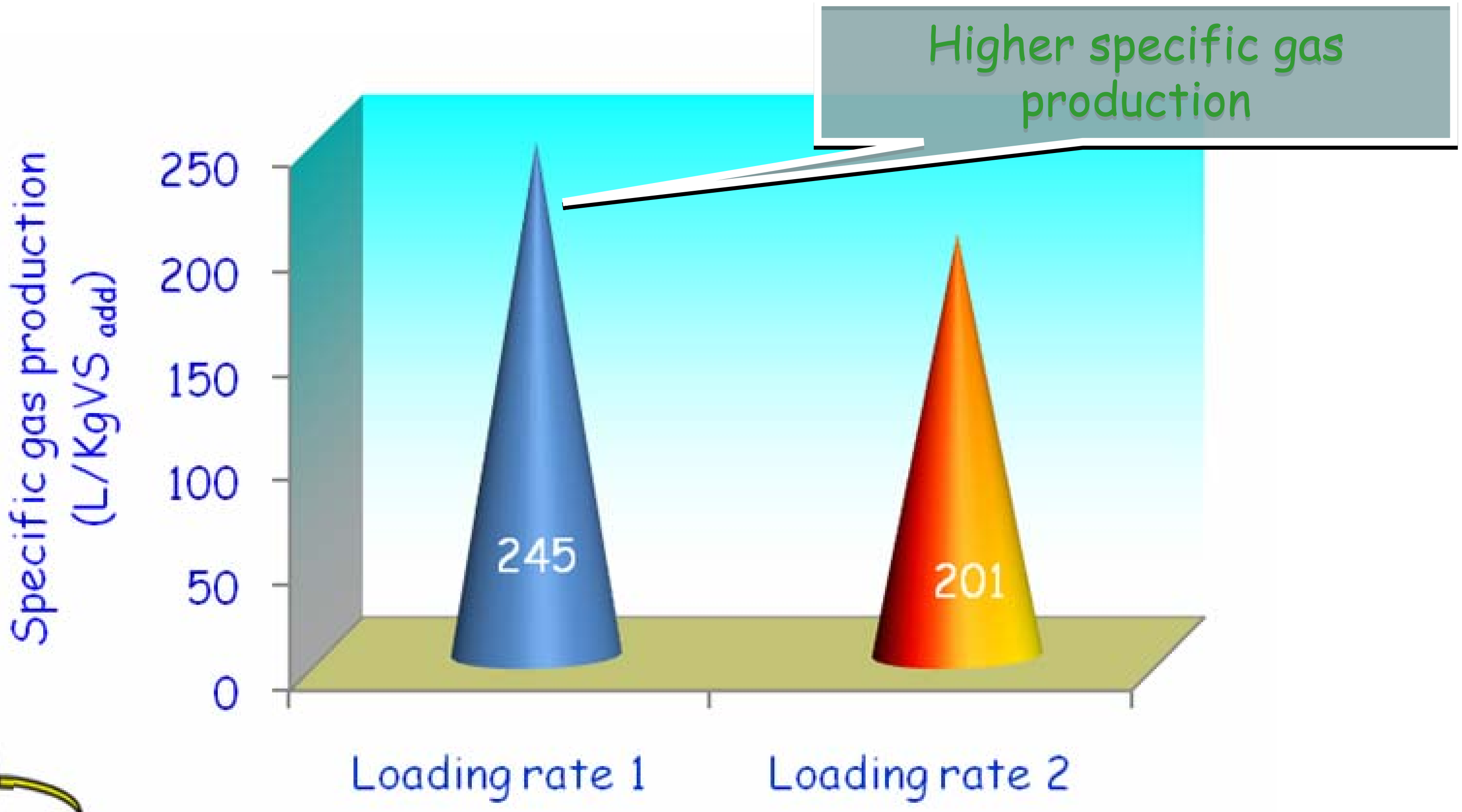
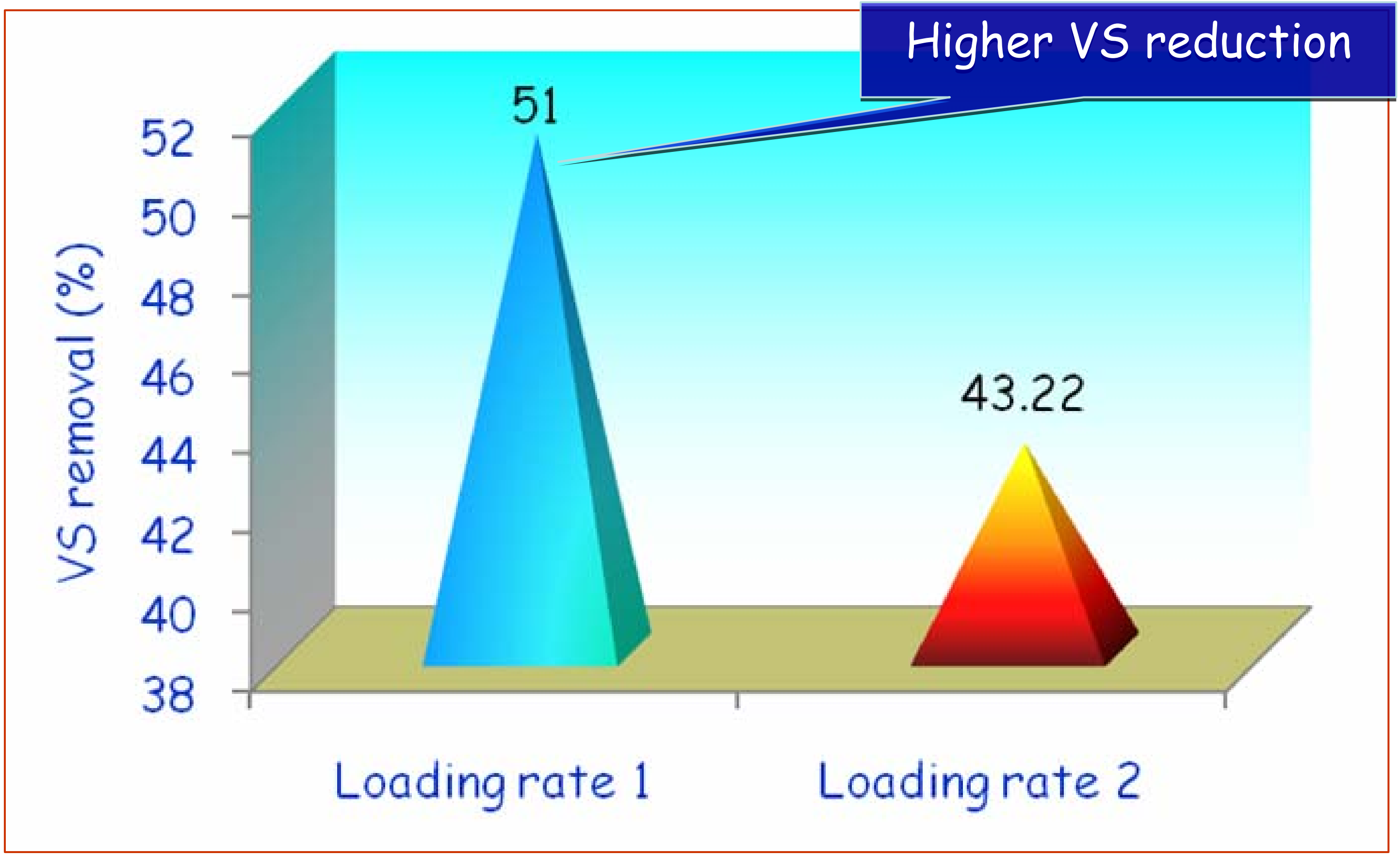
Part 2: Overall Assessment



Part 2: VS Degradation



Part 3: Heavy metals balance

Mn, highest removal efficiency

Heavy metals reduction by sulfide precipitation formed from sulfate reduction

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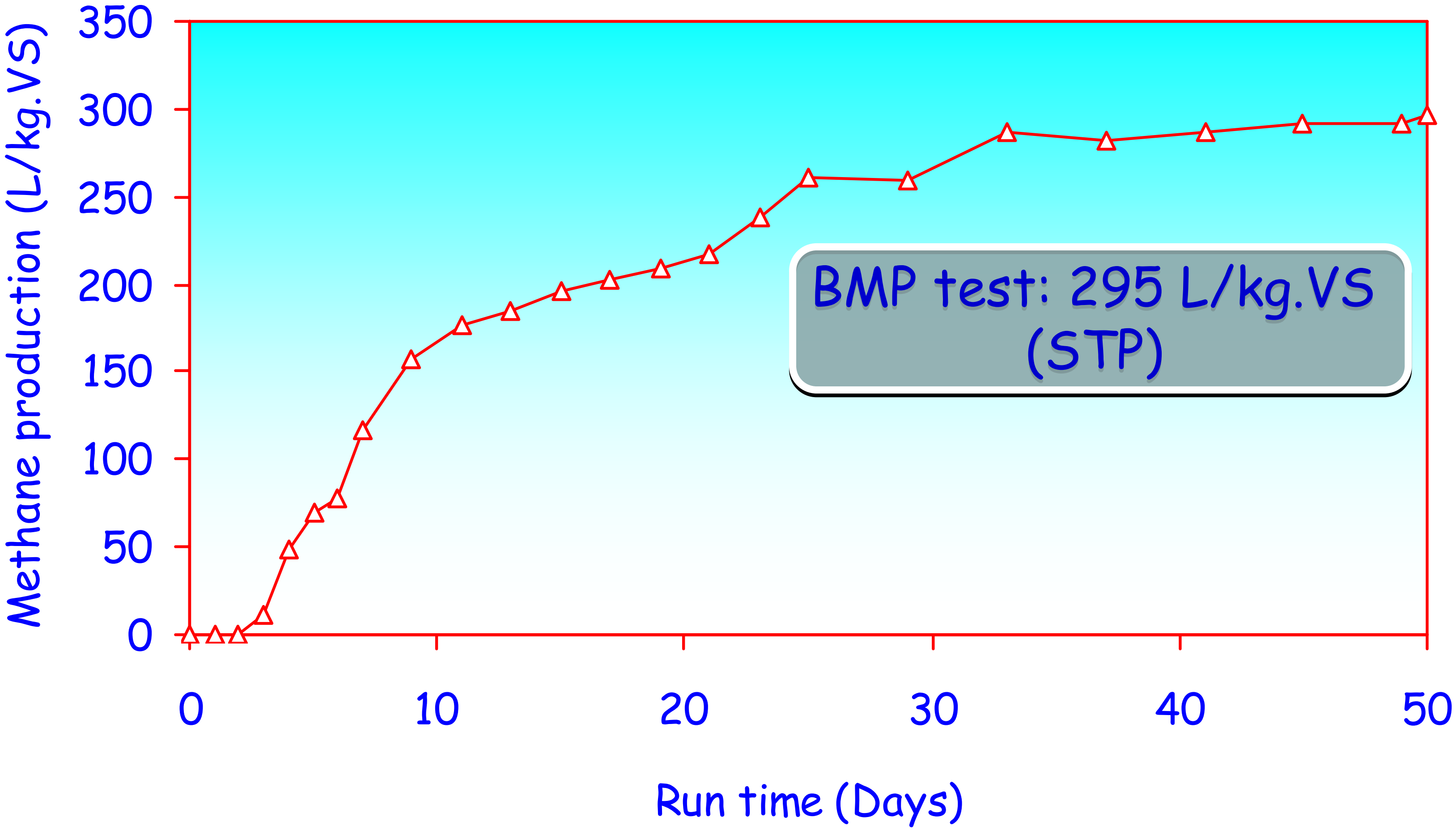
Part 3: BMP Test



BMP test: 295 L/kg.VS (STP)

Part 3: Digestate Quality

Nutrient for fertilizer

	Nutrients (% DM)			C (%)	C/N	Calorific value (MJ/kg)
	N	P	K			
Thai guideline	1	1	0.5	-	<20	15
Digestate	1.09	0.65	0.65	22.75	20.87	11.16

Not only gains the energy, anaerobic digestion also produces a valuable residues for fertilizer purpose. Alternatively, it also has a heating value for potential RDF

RDF potential

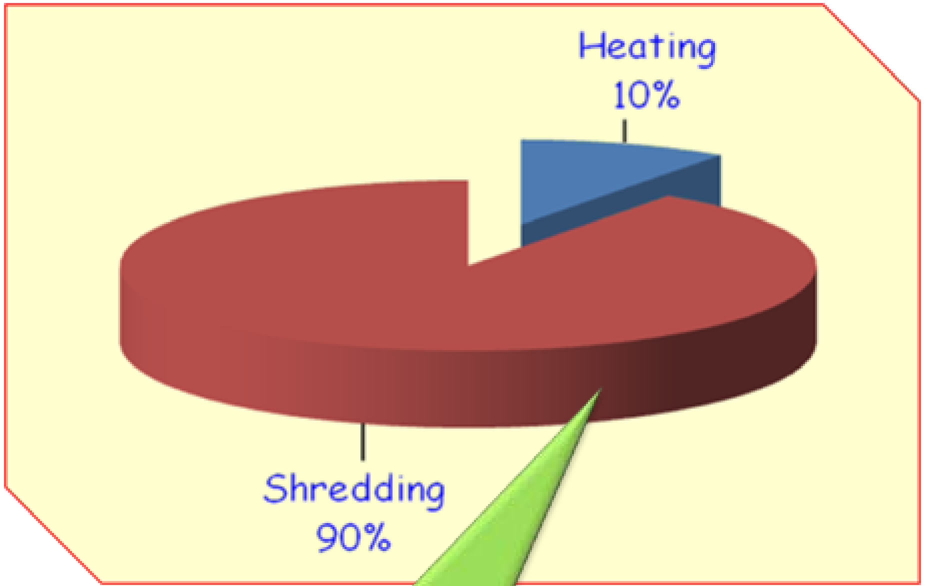
Part 3: Digestate Quality

Less chance of heavy metals contamination (within compost standards) for manually separation feedstock

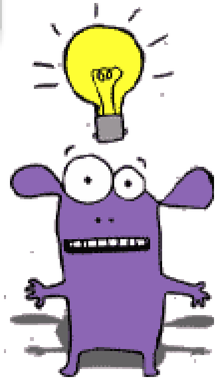
Heavy metals below the standards

	Heavy metals (mg/kg DM)						
	Cd	Cr	Cu	Pb	Ni	Zn	Hg
Dutch standard (Clean compost)	1	50	60	100	20	200	0.3
Dutch standard (Very Clean compost)	0.7	50	25	65	10	75	0.3
WHO standards (Proposed)	3	50	80	150	50	300	-
Digestate	0.64	13.88	54.66	0	12.16	105.74	0.0345

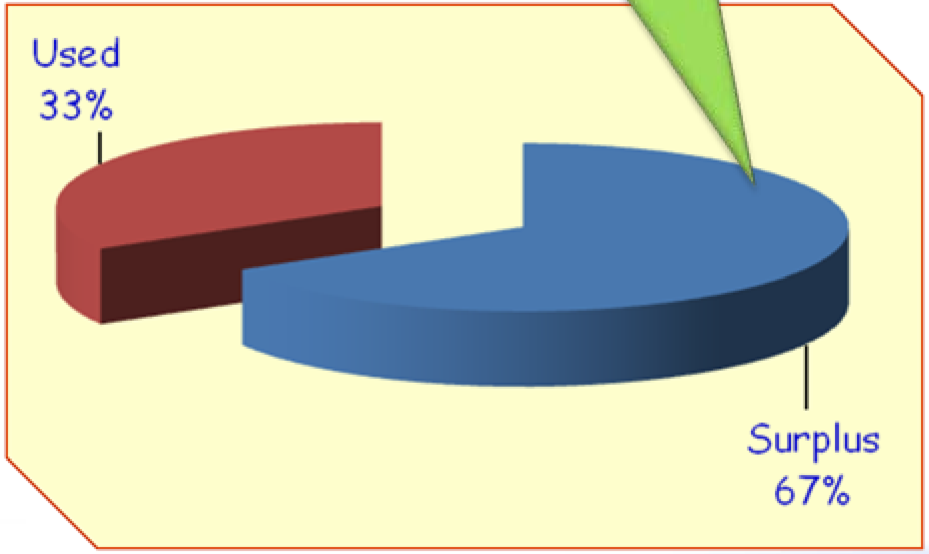
Part 3: Energy Balance-Start-up



High energy for pretreatment



Energy gain, economical value



Conclusions

- Effective starting up the process without inoculum and substrate acclimatization.
- Loading rate 1 gave a higher the biogas production compared to loading rate 2
- Volatile solid degradation of 51% was noticed in loading 1 compared to 43.22% in loading 2.
- A notable energy surplus was gained in start-up.
- End products are stable and has a potential to be used as soil conditioner.
- Calorific value of digestate was 11.16 MJ/kg which has potential to be used as RDF.
- Low amount of heavy metals leached was removed.

Recommendations

- Reactor configuration and modification
  - Option 1: Modify the feeding and withdrawing, and inclination part
  - Option 2: Use 2 stages system called HASL (Hybrid Anaerobic Solid Liquid) bioreactor
- Feeding frequency
- Co-digestion application
- Waste stabilization confirmation: BMP test for residues digestate

Thank You!