SEQUENTIAL BATCH AND CONTINUOUS ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN PILOT SCALE DIGESTERS

by

Radha Adhikari

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

Examination Committee: Prof. C. Visvanathan (Chairperson)
Prof. Ajit P. Annachhatre
Dr. Toshiya Aramaki

Nationality: Nepalese
Previous Degree: Master of Science in Botany
Tribhuvan University
Kathmandu, Nepal

Scholarship Donor: Government of Norway (Norad)

Asian Institute of Technology
School of Environment, Resources and Development
Thailand
May 2006

Acknowledgements

The author expresses her heartfelt thanks and indebtedness to her advisor Prof. C. Visvanathan for his expert guidance, valuable suggestions, and constant encouragement. I value the indefatigable and skillful way in which my manuscript was shaped by him. He was always there when I needed help ready to share his professional expertise during weekends and off-hours too.

The author is gratified by the presence of Prof. Ajit P. Annachhatre and Dr. Toshiya Aramaki as the distinguished thesis committee members, for their valuable critiques and suggestions.

Special thanks are due to research associates P. Kuruparan, and Jenger P. Juanga for their valuable suggestions and inputs. My sincere appreciation goes to Ms Salaya Punshiri, Mr. Tin Win, Ms Suchitra and all staff members of the Environmental Engineering and Management. I would also like to admire extensive assistance from technical staffs, Mr. Panupong Boonyannum and his team whenever asked for. Furthermore, my admiration goes to Khun Dam for his helping hand whenever required. Deep appreciation is extended to my colleagues and friends in Environmental Engineering Program for their help in many ways. My thanks goes to Mr. Tawach Prechthai for helping me in logistic problems. I would like to take this opportunity to thank Dr. Binod Rajbhandari for his career advice. Today, I feel glad that I chose this field of study.

I am thankful to Asian Institute of Technology for awarding me a full scholarship and Norwegian Agency for Development Cooperation (Norad) for financial support that enabled me this great opportunity to get academic knowledge. This admiration is extended to Asian Regional Research Programme on Environmental Technology (ARRPET) phase II project, ‘Sunstainble Landfill Management in Asia’ funded by Swedish International Development Co-opetation Agency (Sida), for partially funding this research.

The author would like to express her deep gratefulness to her beloved husband for his support, understanding and constant inspirations that let this study to accomplish successfully. I appreciate profound understanding of my four years old kids (Priscilla and Supash) and ask their forgiveness for not being able to spend enough time with them during the study period. Last but not the least, I would like to express my gratitude to my loving mother, brothers, and in-laws for their moral support and encouragement.

Finally, I would like to dedicate this piece of work to my late father who always wanted to see me grow academically.

Abstract

Various aspects of Anaerobic Digestion (AD) technology have been the focus of research in recent years. Shortening the digestion time with enhanced process efficiency is one of the integral concerns in AD technology. In line with this concern, experimental investigations were conducted on anaerobic digestion of organic fraction of municipal solid waste (OFMSW) in two different modes of operation, namely; sequential batch anaerobic composting (SEBAC), and continuous anaerobic digestions. Digesters in both cases were pilot scale reactors, and they operated under thermophilic condition. In SEBAC, the pre-stage run was initially operated under mesophiic condition (37 °C) until it stabilized, and the system was shifted to thermophilic condition (55 °C) by gradually increasing the temperature at the rate of 2 °C per day. The process behavior in transient condition revealed that long time acclimatization of inoculums can be avoided if temperature shift is gradual. Three SEBAC cycles were run with the cross-circulation rates of 0.34, 0.46 and 0.58 m^3 leachate / m^3 of waste volume per day for which increasing specific methane yields of 184, 217 and 239 L CH_4 /kg VS, respectively were observed. These values correspond to the 63%, 74%, 82% process efficiency calculated based on the laboratory BMP assay. As the start-up period decreased from 7 days in cycle I to 5 days in cycle III, the digestion time shortened by 5 days. Higher re-circulation rates not only produced higher biogas but also did so in shorter digestion period. The research also reaffirms the earlier findings that the biogas production rate in thermophilic temperature is considerably higher than the mesophilic. In the later half of the research, a simple continuous reactor that operates on draw-feed mode is described. The reactor was operated under thermophilic condition with the feeding rate of 1.9 kg, 2.7 kg, 3.5 kg and 4.25 kg VS/ m^3.day, respectively. The highest biogas production of 1.07 L/day/waste volume was obtained for the organic loading rate of 3.5 kg VS/ m3.day, which slightly reduced to 1.04 L/day/waste volume when the loading to increased to 4.25 kg VS. m^3/day as the system showed signs of over loading. The highest specific gas production observed was 335 L/kgVS for the smallest organic loading rate of 1.9 kg VS/m^3day . The energy balance studies conducted for both SEBAC and continuous digesters indicate that both systems are energy surplus systems. Finally, the residue from AD was tested for its nutrient value, calorific value, and heavy metal contents. The percentage of nitrogen and phosphorus in the digestate confirms that AD keeps the value of nutrients intact for fertilizer and that all heavy metal concentrations fall below the WHO standard (proposed, 1997) of compost for developing countries. The calorific value of the digestate was found to be 13.8 MJ/kg it has potential to be used as Refused derived fuel (RDF).

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AD	Anaerobic Digestion
AOX	Absorbable Organic halide
BMP	Biochemical Methane Potential
OF-MSW	Organic Fraction of Municipal Solid Waste
BVS	Biodegradable Volatile Solids
CAD	Continuos Anaerobic digestion
CH_3COOH	Acetic acid
CH_3OH	Methanol
CH_4	Methane
C_2H_5COOH	Propionic acid
C_3H_7COOH	Butyric acid
C_4H_9COOH	Valeric acid
C/N	Carbon to Nitrogen ratio
CO	Carbon Monoxide
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DM	Dry Matter
GDP	Gross Domestic Product
DOC	Dissolve Organic Carbon
GPR	Gas Production rate
GHGs	Green House Gases
H_2	Hydrogen
HCOOH	Formic acid
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
MC	Moisture Content
MSW	Municipal Solid Waste
N_2	Nitrogen
NH_3	Ammonia
OF-MSW	Organic Fraction of Municipal Solid Waste
OHPA	Obligate Hydrogen Producing Acetogenic bacteria
OLR	Organic Loading Rate
ORP	Oxidation Reduction Potential
ORWARE	ORganic WAste ste REsearch
RDF	Refused-Derived Fuel
SEBAC	Sequential Batch Anaerobic Composting
STP	Standard Temperature and Pressure
SPG	Specific Gas Production
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids

Chapter 1

Introduction

1.1 Background

The environment, in general, has become an issue of global concern in recent years. The most critical environmental problems facing third world cities today is what is referred to as *brown agenda*: lack of safe drinking water, inadequate waste management and pollution control, and interrelationships among environmental problems. The concept of sustainable development has assumed greater significance in this regard. The earth summit declaration, Agenda 21, states that sustainable development needs to be a fully established objective in national and global agenda. Out of many environmental problems, solid waste management is a neglected filed in urban centers of many developing countries. Population growth, industrialization and rapid urbanization have aggravated the problem associated with management of municipal solid waste. Ineffective and inappropriate solid waste management is responsible for myriad of problems including environmental pollution, degradation of sanitation, unhygienic living conditions etc.

Waste management practices are continually changing. Technical requirements for waste management facilities are becoming more stringent. Regulations in many countries now require that landfills have engineered safeguard such as liners, leachate collection system, gas management, and environmental monitoring system. These new technical requirements not only increase the cost but also public scrutiny of proposed projects. Government procurement policies in many developed countries are now stimulating recycling markets. Source reduction, recycling, and composting are now well integrated in the waste management system. Even with an extensive recycling program, there will always be organic fraction remains in the waste stream to be disposed. Land filling is a cheap and a simple waste management practice but various potential risk and associated hazards could create imbalance ecosystem.

Increased environmental awareness and the concerns over the problem from landfilling have stimulated new approaches to treatment before disposal. Aerobic and anaerobic biological processes have been used as pre-treatment technologies for volume reduction and stabilization of solid waste prior to landfilling. Anaerobic digestion is an effective means for treating the organic fraction of solid waste since it can convert the biodegradable fraction of the waste into high methane content, biogas and stable residue that can be upgraded to compost quality. The importance of anaerobic digestion as pre-treatment of waste prior to landfilling has been realized because there is growing interest in solving both waste excesses and energy shortages by using anaerobic digestion.

Organic fraction of municipal solid waste (OFMSW), because of its unique characteristics such as low heating value and high moisture content, make it undesirable for combustion. Moreover, combustion causes air pollution problem, and requires high maintenance and operating cost. Interestingly, OFMSW is ideally suited for bio-process technology treatments. The biological process involves making use of specialized microorganisms to perform the desired degradation. Anaerobic digestion and aerobic composting both, are, biological process for the recovery of nutrients from the organic fraction of municipal solid waste (MSW). Anaerobic biodegradation of organic material proceeds in the absence of oxygen and is the consequence of a series of metabolic interactions among various groups of microorganisms. The anaerobic system generates energy in the form of methane to operate the process and have enough surplus energy to market. Conventional composting, on the other hand, consumes energy to aerate. Further, aerobic composting requires mixing and produces foul odor.

Landfills are the source of large emissions of methane to the atmosphere, and methane gas has a global warming potential that is over twenty times that of carbon dioxide. Because of the problem associated with the use of fossil fuel and increasing energy prices, there is a need for a sustainable clean energy source. Biogas, in this regard, becomes very attractive as it is a clean renewable energy source. Utilization of biogas energy can reduce carbon dioxide emissions. Anaerobic digestion produces compost which can be used as organic fertilizer, thus, lessens the energy requirement to produce inorganic fertilizer.

As a mechanized industrial process, anaerobic digestion has been used for almost a century for the bio-stabilization of sewage sludge. The digestion process has proved useful to the wastewater industry, in that, the net energy production from the release of methane gas can be harnessed to power other unit operations used in the treatment of wastewater. Although the anaerobic treatment of sewage sludge is a well-recognized technology bringing benefits to the wastewater industry in the form of energy and reduced volumes of sludge, it is only over the last decade that attention has been seriously focused on the use of mechanized processes for the controlled digestion of solid wastes in purpose built reactors. Even today, the number of plants that are operational is limited as there is still uncertainty regarding process economics and reliability; yet adaptable technology and new research are beginning to open up this market.

Anaerobic digestion (AD) has demonstrated to be a viable option for the management and stabilization of the biodegradable fraction of waste. From life cycle assessment (LCA) prospective also, AD shows the very best LCA of all renewable energies like wind, water etc. (ESU service 2000). In life cycle assessment using eco-indictor method, AD also showed an excellent LCA performance as compared to other treatment technology like composting, incineration (Edelmann et al., 2004).

Reduction in the volume and mass of solid waste is a crucial issue especially in the light of limited availability of final disposal sites in many parts of the world. Although numerous waste and byproduct recovery processes have been introduced, anaerobic digestion has unique and integrative potential, simultaneously acting as a waste treatment and energy recovery process. Anaerobic digestion can provide substantial solutions both in energy generation as well as in environmentally sound byproduct recovery and waste treatment. Due to its integrative potential, it has emerged as a key technology contributing to sustainable development. Use of biogas as energy source helps offset the green house gases emissions associated with energy production using fossil fuel. It can reduce the global warming problem world is facing today. In the past, long residence time and unpredictable feed have limited the application of AD, but current research has lead to expanding markets.

1.2 Problem statement

Several approaches are available for anaerobic digestion. An anaerobic process can be low solids or a high solids process, single stage or multi-stages operation process, batch process or continuous process depending upon the amount of solids contents and mode of operation. The low solids anaerobic process, typically consists of less than 10% of solid contents, and is referred to as wet process. The drawback of the wet process is that it requires large amount of water resulting into higher reactor volume and expensive post-treatment technology. A high solids system, referred to as dry process, allows higher solid contents (20-60%) and, therefore, requires smaller reactor. Although the dry process recovers higher methane production, it results into accumulation of volatile fatty acids during start up. The volatile fatty acids (leachate) formed in the start-up process may cause the digester failure. To overcome this problem two-stage anaerobic system has been developed in which the hydrolysis/ acidification phases are optimized in a separate reactor and overall stability of the process is achieved. Digester failure can be avoided because of the removal of volatile fatty acids (leachate) formed in the start-up process. The two stage AD involves separate stages of AD, thus, provides flexibility to optimize reactions, allows investigation of the intermediate step in the digestion, and helps control the failure of the reactor.

Anaerobic digestion is classified into two processes based on the stages of operation; namely batch and continuous process. In a batch process, 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 Sequential Batch Anaerobic Composting (SEBAC) process uses a combination of high solid fermentation and leachate recycling between new and mature reactor to provide moisture, nutrients and inocula for rapid start-up (Chynoweth et al., 1992). On the other hand, a continuous reactor vessel is continuously fed with feedstock and fully degraded material is continuously removed.

The main difference between batch and continuous methods is that in the batch process, the steady state situation is never reached, whereas, in the continuous process, this is a pre-condition. Although the system is technically simple and less capital intensive land required for a batch processes is considerably larger. Besides, the batch system is not practical as the waste generation is a continuous process. Moreover, loading and unloading is another major concern in batch process. Because of these shortcomings, batch system up to now has no been able to succeed in taking a substantial market (Bouallagui et al., 2005). This has prompted the researchers to design a system that can take continuous feedstock in put (Mtz. Viturtia et al., 1995). Importantly, the higher initial investment cost may be compensated from real state cost reduction where the land is scarce.

Creating a thriving anaerobic climate requires maintaining a consistent temperature and quality of organic matter within a sealed and airless container. The anaerobic digestion process is more chemically complex and technically demanding. Researches have proved that biogas production is relatively low under mesophilic condition (37 °C) than thermophilic condition (55 °C). Besides, digestion period can be considerably shortened under higher operating temperature (Juanga, 2005; Cecchi 2003). In view of these findings, both SEBAC and continuous process in this research are conducted under thermophilic condition.

1.3 Objectives

The primary objective of this research is to reaffirm anaerobic digestion process as a sustainable pre-treatment technology to reduce mass and volume as well as stabilization of organic fraction of municipal solid waste (OFMSW) prior to landfilling. This will be achieved from sets of experimental investigations using batch and continuous reactor systems. The specific objectives are:

- To investigate the performance of sequential batch anaerobic composting (SEBAC) of OFMSW in thermophilic temperature at different cross-circulation rates.
- To design and operate a continuous system of anaerobic digestion that will be able to sustain continuous feedstock and to optimize the rate of organic loading.
- To study and investigate post treatment technologies suitable for the digestate waste and to explore the possibility of utilization of such wastes for its economic value.

1.4 Scope and Limitations

- Experimental investigations were conducted in two modes namely; continuous mode and batch mode in pilot-scale digesters.
- The research focused on pretreatment of organic fraction of municipal solid waste (OFMSW) collected from Taklong municipality dumpsite, Pathumthani province of Thailand.
- Experiments were conducted under thermophilic condition temperature (55°C).

Chapter 2

Literature Review

2.1 Introduction

Sanitary landfills, as a method of disposal, have been considered the most economical and dependable system of waste management. However, population growth, resource limitation along side the rapid urbanization and industrialization, have aggravated the problem of management of solid waste, and indicated that the landfilling approach may not be sustainable. The urban population in Asia, which is 37% of the total population, generates 760,000 tons of municipal solid waste per day, and this is expected to rise up to 1.8 million tons by 2025 (Pokharel & Viraraghavan, 2005). The municipal solid waste (MSW) production in developed economies has also grown continually. Strong correlation between MSW generation and Gross Domestic Product (GDP) confirms a strong link between affluence and MSW quantities (Ludwig et al, 2003). It has been realized that the traditional landfilling system, hitherto considered the most economical and common practice of waste management, if practiced without envisioning its stability and behavior, can create detrimental environmental problem.

The sustainability of the landfilling system has become a global challenge due to increased environmental concerns. With the current practice of direct landfilling in the developing countries and resulting environmental consequences, the method seems to be unattractive and landfilling of organic even prohibited in some European countries for example Denmark (Hartman et al., 2004). It is now generally agreed that direct landfilling is not environmentally sound approach wherein various potential risk and associated hazards could create imbalance ecosystem. Nevertheless, landfill plays an indispensable role in integrated solid waste management systems since it is the ultimate destination of waste. Even with implementation of waste reduction, recycling, and transformation technologies, landfill still remains an important part of the integrated solid waste management.

The organic fraction of the municipal solid waste (OFMSW) causes the emergence of harmful pollutants, and therefore, treatment of OFMSW is essential to minimize environmental degradation. In this connection, the importance of pre-treatment of waste prior to landfilling has been realized in recent years. The biological pretreatment of the waste in combination of landfill is a useful and viable technology that not only improves landfill behavior but also preserves the environment with resource recovery.

Pre-treatment of waste prior to landfill includes mechanical as well as biological processes. Mechanical pretreatment (sorting, shredding, etc) increase the specific surface area of the waste and enhance the biological process (Leikam & stegmann, 1999). Available biological pre-treatment technologies include aerobic composting and anaerobic digestion. Anaerobic digestion is an effective means for treating the organic fraction of solid waste since it can convert the biodegradable fraction of the waste into high methane content, biogas and stable residue that can be upgraded to compost quality. The anaerobic digestion (AD) is widely-used technology in Europe (Chavez-Vazquez & Bagley, 2002). The technology is promising to Asian countries because of the waste characteristics that suit the AD process. The composition of MSW stream in Asian cities shows high (>50%) biodegradable organic fraction (Visvanathan et al., 2004).

This chapter begins with the current state of MSW generation in Asia, and describes briefly the AD process fundamentals, operational conditions, limitations and performance of parameters. Wide ranges of articles are reviewed covering a role of anaerobic digestion on integrated solid waste management.

2.2 Solid waste generation in Asia

The quantity and composition of MSW generation depends on location, season, economic conditions, and several other factors. With high economic growth and rapid urbanization, MSW generation in Asia is likely to rise significantly. Visvanathan et al. (2004) reported that the generation trend situation of the selected Asian countries showed an increasing solid waste production with time. The individual components that make up a solid waste stream and their relative distribution are important factors in evaluating technological needs and management of the programs and plans. The potential for changes in composition in future also plays an important role in decision making process. Das et al., (2002) reported that over 69 % by weight of MSW in USA is composed of biodegradable fraction such as paper, food waste and woody debris, a typical example of an affluent society. Likewise, major portion of the MSW generated in most Asian countries is also dominated by biodegradable organic fractions composed of food wastes, yard wastes and mixed paper (Visvanathan et al., 2004). As illustrated in Figure 2.1, food wastes dominate over other waste fraction in most developing countries in Asia like China, India, Sri Lanka and Thailand.

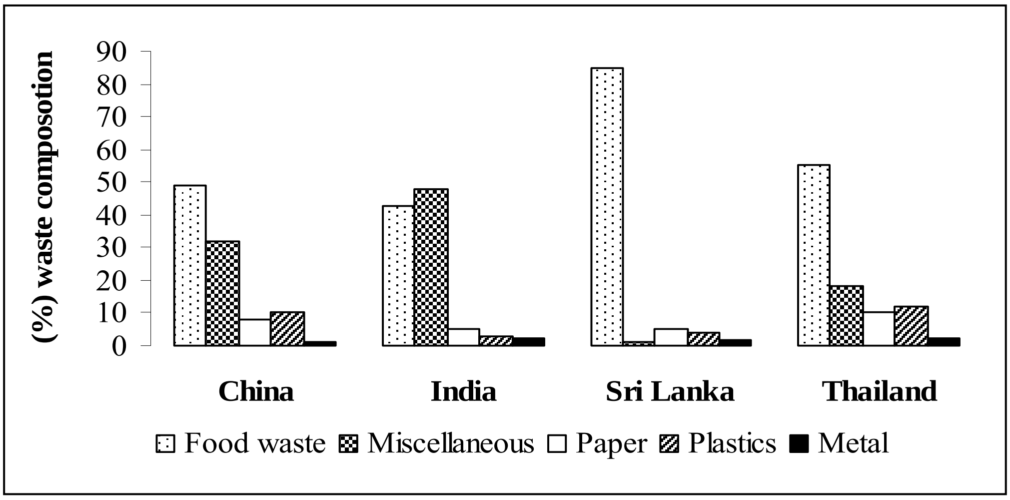


Figure 2.1: MSW composition of selected Asian countries

The organic fraction of the waste is usually obtained from the commingled or unsorted waste in three main pathways namely; mechanical selection, source sorting and separate collection (Mata-Alvarez, 2003). They present special challenges for disposal because of the fact that in many places landfills are approaching their design capacity and due to their environmental impacts, many are facing closure. However, the organic fraction of MSW has also generated much interest among researchers as they are considered potential sources of energy and biogas production (Gunaseelan, 1997).

2.3 Landfills and associated problems

Sanitary landfill refers to an engineered facility for the disposal of MSW designed and operated to minimize public health and environment impact. Modern sanitary landfills are designed with impervious liners, and leachate collection, removal, and treatment facilities to minimize the potential for groundwater contamination. However, even modern landfills with state-of-the-art technologies would probably leak within a few decades of their closure. Nevertheless, fugitive release of landfill gases occur even in highly engineered system. In this regard, post closure monitoring is necessary and requires additional investment. Biotransformation in landfills is a very slow process, and may continue over years and may require several decades for completion. Anaerobic fermentation in landfills extends for periods of 20-40 years and it takes decades to reach 50% for the methane content (Vieitez et al., 2000). Because of lasting detrimental environmental problems landfill becomes unattractive.

The decomposition of the wastes generates gases such as methane, carbon dioxide, vinyl chloride, and hydrogen sulfide which slowly seep into the air around the landfill. This impairs air quality in the immediate vicinity and, on a larger scale, contributes to the greenhouse effect and global warming. Leachate is generated by percolating rainwater and uncontrolled run-off of organic and inorganic compounds resulting in the contamination of soil, surface and groundwater. The pollutants include dissolved organic matter, inorganic macro-compounds (calcium, magnesium, sodium, potassium etc.), heavy metals (cadmium, copper, chromium, lead), and xeno-biotic organic compounds (aromatic hydrocarbons, phenols, etc). It has been estimated that groundwater pollution originating from landfills may be at risk even after several centuries (Ludwig et al., 2003). Problems associated with landfills, in general, are summarized as:

- Requirement of post-closure monitoring system demanding additional investment.

- Rainwater infiltration generates leachate which contains organic and inorganic compounds. This results in combination of soil and water pollution. Importantly, leachate generated at any point in time constitutes leachate derived from solid waste at different stages, and therefore, it exacerbates the soil and ground water contamination.

- Landfill gas consists of methane, carbon dioxide and traces of non-methane volatile organic carbons. These gases lead to ozone depletion and eventually global warming effect. Further, the possibility of landfill gas (methane) explosion, especially in the absence of post monitoring and improper landfill gas collection system. Visvanathan (2004) compared emission tendency from different types of landfill with time and concluded that traditional landfill poses long term critical emission problem. Even with the engineered landfill system, leakage from liners and cover materials can not be guaranteed in long run.

- The settlement of the waste due to the decomposition of the high content of organic materials in landfills. This could be considerable affecting the integrity of the cover system with potential cracking, and consequent water infiltration, and the gas migration. Due to the heterogeneous characteristics of the solid waste, strength parameters such as friction angle and cohesion are difficult to determine.

Consequently, geotechnical landfill (in) stability remains potential source of risk (Kosch & Ziehmann, 2004).

- Landfills require large areas. The existing landfill sites are nearly exhausted and new landfill sites are hardly available because of the shortage of utilizable land and the objection of residents near the proposed landfill sites.

- Aesthetics problems, foul odor, nuisance from scavenging animals.

Despite existing and foreseeable problems associated with landfills, landfills are indispensable part of the solid waste management schemes. Incineration and pyrolysis technologies are capital intensive and they present problems of air pollution. Recycling and reuse may effectively reduce the amount of waste; there still is an organic fraction that remains in the waste stream to be disposed.

2.4 Sustainable and integrated solid waste management

An integrated solid waste management is defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals. The integrated management plan includes source reduction, reuse, recycling, recovery, incineration, treatment and landfilling. The approach seeks to maximize the useful life of the resources involved. A sustainable approach to waste disposal is the one that is based on three fundamental principles; namely protection of health and environment minimizing the burden to future generation and conservation of resources.

Source reduction has an objective of reducing the amount of waste at the source itself. Reusing involves the use of material in the same form and recycling deals with converting the waste materials into new forms. The reusing habits and recycling strategy create a broader option in waste management. The incineration and pyrolysis destroy putrescible and significantly reduce the volume of waste. As public awareness increases and technologies improve, the amount of reused/recycled and incinerated materials is expected to increase with time. However, there would always be remaining waste residues that couldn’t be recycled and incinerated. In this regard, pretreatment technologies prior to landfill were begun to explore. Thus, landfill remains and will remain an inescapable component of integrated solid waste management strategy (Chugh et al., 1999).

2.5 Pre-treatment technologies

Landfill pre-treatment may be broadly defined as any process that will alter the composition or characteristic of the waste stream prior to landfilling. The primary objective of the pre-treatment is to control/minimize the landfill emissions and reduced the weight/volume of the waste to be disposed. Therefore, the pre-treatment process brings about mass and volume reduction and saves valuable landfill spaces and shortens the unpredicted after closure monitoring period. Pretreatment prior to landfill could stabilize and reduce the waste volume inside the landfill in higher degree and in short period of time compared to the wastes that were directly landfilled as illustrated in Figure 2.2. The landfill pretreatment of MSW was introduced to the integrated solid waste management system only recently and has so far been practiced in very few countries.

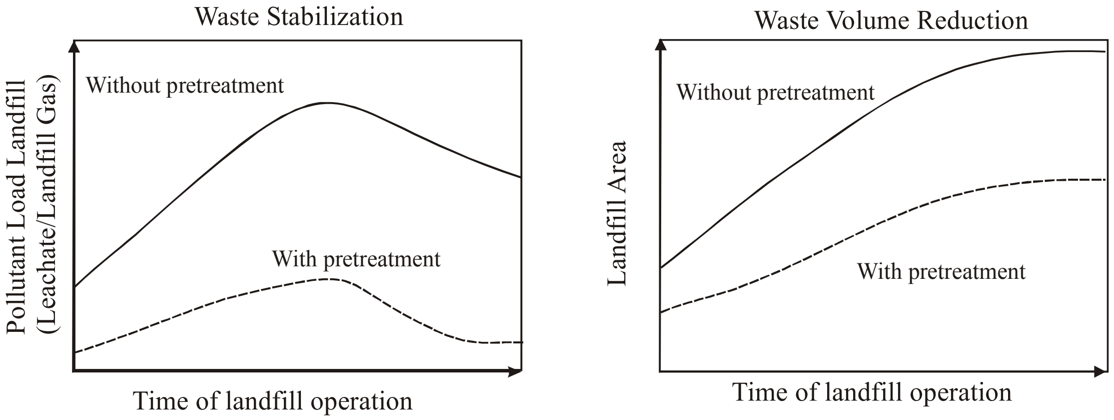


Figure 2.2: Representation of the importance of pretreatment in terms of waste stabilization volume reduction with time

Pretreatment of waste can be attained either from mechanical or from biological process. Shredding, screening, sorting and separation of ferrous components are some of the mechanical processes commonly available. Mechanical pretreatment reduces volume and increase specific area of the waste. As a result, performance of biological pretreatment step is enhanced and stabilized (Leikam & Stegmann, 1999). Biological pretreatment stage involves degradation of organic fraction of solid waste into useful end products with resource (biogas) recovery.

There are two alternatives when it comes to microbial degradation of organic waste, aerobic degradation, often called composting, and anaerobic degradation. These technologies are commonly used to transform the organic fraction of MSW into conversion products (gas, solid and liquid). However, composting as a sole means of biowaste treatment achieves less reduction in biowaste volume then by anaerobic digestion, and consequentially volume of the compost is corresponding marketing or disposal arrangements are less easily managed. Both of these processes have a place in solid waste management as each process offer distinct advantages. In aerobic degradation, oxygen is used as the final electron acceptor, and the main part of the energy in the organic substrate is made available to the cell as the organic carbon is oxidized to carbon dioxide. Characteristic for aerobic degradation is that of the order of 60% of the energy of the substrate is used for cell maintenance and growth, and the rest is converted into heat. This is reflected in the carbon balance, where approximately half of the carbon is used for cell growth, the rest being converted to carbon dioxide. In anaerobic degradation, most of the energy in the substrate is retained in the degradation product, methane, and does not become available to the microbes. In anaerobic degradation it is generally said that 90% of the energy in the substrate is retained in the methane, 5% is lost as low-grade heat and only 5% is available for cell maintenance and growth (Colleran, 1992). This is reflected in the carbon balance, where only 5% of the carbon in the substrate is incorporated into new biomass. The rest is converted into carbon dioxide and methane.

Although anaerobic operation is more complex, it is known for its wide spectrum of advantages, the benefits of energy recovery and methane gas production, in particular. Details on relative merits and demerits of these processes and fundamentals of anaerobic digestion process are presented in the following section.

A combined mechanical and biological pretreatment process could be a viable approach to tackle landfill problems. Trankler et al. (2004) suggested a mechanical biological processing as a feasible pretreatment option for pollution reduction from landfill. Visvanathan (2004) listed the following salient features of such a process:

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

2.5.1 Aerobic composting

Biological treatment of solid waste by simple composting is one of the applicable methods among the available technologies for pre-treating of MSW. Aerobic processes offer the advantage of relatively simple operation Aerobic composting needs proper aeration to provide sufficient oxygen for the aerobic microbes to stabilize the organic waste. An Aerobic process is, therefore, a net energy user; it requires 30 kWh energy input per ton of waste (Mtz.-Viturtia et al. 1995). Generally aerobic composting requires significant area of land, 1.5 to 2 acres, for a plant with 50 ton/day capacity (Tchobanoglous et al., 1993). Odor problems in composting can not be neglected. Recently, combining an anaerobic process with composting is getting acceptance as to make a positive energy balance by capturing methane from organic decomposition.

2.5.2 Anaerobic digestion

Anaerobic digestion is the biological breakdown of organic materials in absence of oxygen. It is carried out by anaerobic micro-organisms. They convert carbon containing compounds in to methane and carbon dioxide with trace amount of other gases. The remaining material is partially stabilized material that can be cured and used as compost. The treatment of solid waste by anaerobic digestion uses this biological process in controlled environment. Anaerobic digestion reduces the organic content of waste by 30-60% (Polprasert, 1996). According to Mata-Alvarez (2003), among biological treatments, anaerobic digestion is frequently the most cost-effective, owing to the high energy recovery linked to the process and its limited environmental impact.

2.5.3 Aerobic versus anaerobic

Aerobic composting is the decomposition of organic wastes in the presence of oxygen; the end products of biological metabolism are CO_2, NH_3, and H_2O. Anaerobic digestion, on the other hand, is the decomposition of organic wastes in the absence of oxygen; the end products are CH_4, CO_2 and H_2O. The aerobic composting is essentially an endothermic process whereas the anaerobic digestion is an exothermic process. Both processes offer distinct advantages and they have their own place in waste treatment technologies. However, as a pretreatment technology, anaerobic digestion provides the following salient features.

- Anaerobic digestion offers higher flexibility in treating different types of waste streams, ranging from wet to dry and from clean to grey waste (Baere, 2000).

- While lignified wastes are more suitable for aerobic composting, wastes with higher moisture content (wet) and higher biodegradability, are suitable for anaerobic digestion. Besides, humid wastes can cause odor problem in composting facilities (Edelmann and Engeli, 1993).

- Anaerobic process offers the benefit of energy recovery in the form of methane gas and thus is net energy user. Anaerobic digestion produces 100-150 kWh energy per ton of product while aerobic composting uses 30-35 kWh per ton input (Braber, 1995). In addition, the production of renewable energy has positive consequences because of saving of or compensation of non-renewable energy. The process energy requirement in anaerobic digestion and associated operation is typically less than 10% of methane product (Chynoweth & Pullammanappallil, 1996).

- Although the investment costs for anaerobic digestion are a factor of 1.2-1.5 higher than for aerobic composting, the recovery of energy (100-1,500 m^3 biogas per ton of biowaste) is an important factor, particularly in third-world countries (Biey et al., 2003).

- In anaerobic digestion, under controlled environment (reactor), greenhouse gases (GHGs) are collected and utilized. However, with composting, methane is released during the initial stage at which anaerobic process prevails.

- For anaerobic composting improved water management is necessary to avoid the run off of leachate and to prevent anaerobic condition in the compost pile (Six & De Baere, 1992).

- In the aerobic composting process, the biowaste is aerated for 12 weeks, while the combined anaerobic/aerobic composting process consists of a 3-week anaerobic digestion period (phase I) and a 2-week aeration period (phase II) (Mata-Alverez, 2000). Total digestion time requirement for composting is about 12-16 weeks or longer depending upon the target values (Stegmann, 2005).

- Relatively more retention time requirement for solely composting inevitably necessitates a large area requirement for the operation.

2.6 Environmental and life cycle assessment perspective

Methane emission from landfill is a considerable fraction of total green house gas emission. The significance of methane is influenced by the fact that the global warming potential of methane is 21 fold than that of carbon dioxide. For the abatement of green house effects, the waste sector is easily managed and requires less effort in comparison to the energy sectors (Ayalan et al., 2000). Of the green house gases, methane is an excellent candidate for control because of its short atmospheric lifetime (Chynoweth, 1996).

The ever increasing growth in global energy consumption, increasing energy prices, limitations in fossil fuels being non renewable resources and environmental problems associated with combustion, have led to the search for new and renewable energy sources. With increased levels of waste production, limited area available for land filling, and increased awareness of environmental impact, alternative methods are being explored.

Uncontrolled landfills, lagoons or stock poles release undesirable methane to atmosphere. However, anaerobic digestion can capture methane which otherwise would be released into the atmosphere. Besides, AD helps to offset bad smells and flies, improves health and hygiene, and generates income through compost and energy recovery (Taleghani & Kia, 2005). The feed stock for AD being a renewable source has no depletion time unlike fossil fuel. It can reduce global warming potential by lowering the demand of fossil fuel. As the digestate can be used as soil conditioner after post treatment, the energy consumption in fertilizer manufacturing could be reduced (Monnet, 2003).

Eriksson et al. (1999) used a calculation model, ORWARE (ORganic WAste REsearch), based on life cycle assessment of the material and energy flow with the various combination of waste treatment options. Based on the case study on three Swedish municipalities, it was revealed that composting was comparable to the anaerobic digestion but gave higher energy use and environmental impact. It was recommended that combination of anaerobic digestion; material recycling and incineration provide the best solution to reduce land filling in terms of both environmental impact and cost.

Edelmann et al. (2000) compared six different technologies to treat 1000 tons of biogenic waste per year using life cycle assessment tool. From ecological point of view, anaerobic digestion with an aerobic post treatment showed the best performance over composting, incineration or combination of digestion and composting. Life cycle based assessment of the major environmental impact of MSW have shown benefits from MSW energy recovery by reducing greenhouse emissions, reducing acid gas emissions, reduced depletion of natural resources (fossil fuel and materials) and reduced impact on water and land (IEA, 2003).

2.7 Principles of anaerobic digestion

The anaerobic digestion is a controlled process of microbial decomposition involving consortium of microorganisms which decompose organic matters in series of steps that ultimately produce methane and carbon dioxide as terminal products. Anaerobic digestion process involves bacteria and archaea, which play an important role in waste decomposition. Generally, anaerobic digestion process consists of four stages namely; hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Figure 2.3 illustrates theoretical stages involved in anaerobic digestion.

2.7.1 The process fundamentals

1. Hydrolysis

The fist step in AD is hydrolysis. The complex polymeric solid substrate is hydrolyzed into their respective monomers: protein into amino acids, carbohydrate into simple sugars, and fat into long-chain fatty acids by hydrolytic enzymes (lipase, protease, cellulase, anylase, etc.) secreted by microorganism. The rate of hydrolysis is the function of factors such as pH, temperature, composition, and size of the substrate and high concentration of intermediate product. The microorganisms producing these enzymes can be obligate or facultative anaerobes. When the substrate is in particulate form, hydrolytic bacteria can be inhibited by accumulation of sugars and amino acids (Mata-Alvarez, 2003). It is commonly found that hydrolysis is often the slowest and limiting-step in anaerobic degradation process for solid substrate (Schieder et al., 2000).

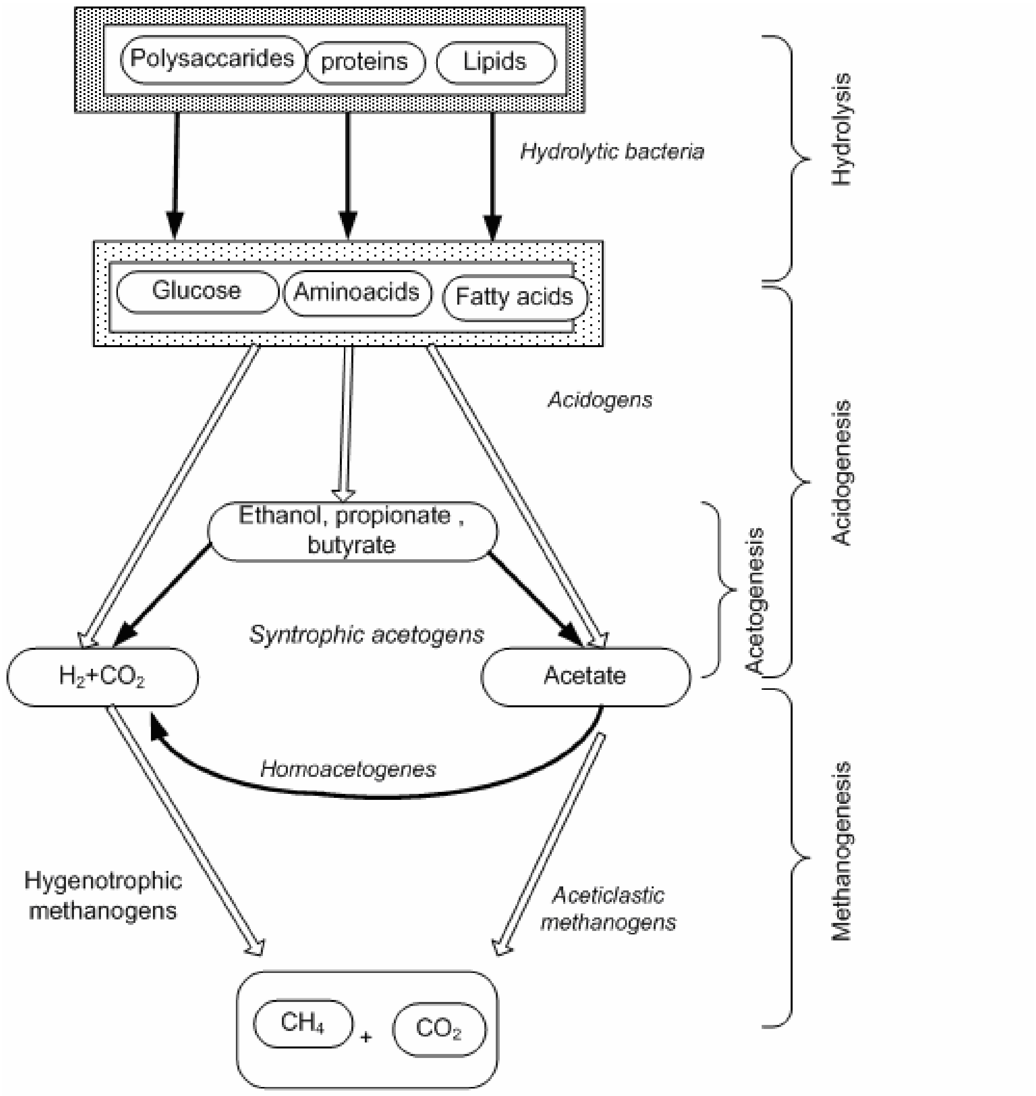


Figure 2.3: Schematic representation of anaerobic digestion process showing various theoretical stages involved

2. Acidogenesis

Hydrolysis is followed by acid-forming phase of acidogenesis. Soluble organic components including the products of hydrolysis are converted into volatile organic acids (propionic acid, lactic butyric, succinic acids), ketones, aldehydes, formate, acetate, carbon dioxide and hydrogen by the action of acid forming (fermentative) bacteria known as acidogens. These organisms comprise a wide variety of different bacterial genera representing both obligate and facultative anaerobes. In a stable anaerobic digester, the main degradation pathway is via acetate, carbon dioxide and hydrogen, and the reduced fermentation intermediates play a minor role (Schink, 1997). This degradation pathway also gives a higher energy yield for the microorganisms, and the products can be used directly as substrates by the methanogenic microorganisms. The accumulation of product such as lactate, ethanol, propionate, butyrate and higher volatile fatty acids (VFAs) is the bacteria’s response to increased hydrogen concentration (Schink, 1997). These products can not be utilized directly by the methanogens, and must be degraded further by the obligate hydrogen-producing bacteria in a process that is referred to as acetogenesis.

The products depend upon the type of bacteria as well as environmental condition such as temperature and pH. Microorganisms responsible for fermentation are *Bacteroids succinogens, B. fibrisolvens, Rumen spirochete, Acetivibrio cellulolyticus, Clostridium thrmocellum, Clostridium butyricum* etc. The chemical reactions involved are:

$$C_6H_{12}O_6 \rightarrow 2CH3\ CH_2OH + 2\ CO_2$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH3\ CH_2CH_2OH + 2H_2O$$

2. Acetogenesis

Both long chain fatty acid (hydrolysis products) and volatile fatty acid (acidogenesis products) are converted into acetic acid, formate, hydrogen and carbon dioxide by Obligate Hydrogen Producing Acetogenic bacteria (OHPA). This intermediate conversion is crucial for the successful production of biogas, since these compounds can not be utilized directly by methanogens. Acetogens are slow growing and suffer from a thermodynamic product inhibition by hydrogen gas or formate and that their growth rate depends upon simultaneous removal of their own metabolic products that normally depend upon activity of methanogens (Boone et al., 1993). The reaction proceeds if the hydrogen partial pressure is low enough thermodynamically to allow the conversion in order for acetogenic degradation to yield energy. Thus, acetogenesis is achieved by syntrophic associations with hydrogen-consuming methanogens. Syntrophy means, literally, "eating together" and refers to the interdependence of the hydrogen producing and hydrogen consuming organisms. Under standard conditions, the presence of hydrogen in the solution inhibits oxidation. The reaction proceeds if the hydrogen partial pressure is low enough thermodynamically to allow the conversion. The presence of hydrogen scavenging bacteria that consume hydrogen, thus lowering the partial pressure, is necessary to ensure thermodynamic feasibility and the conversion of all the acids. Therefore, partial pressure of hydrogen is an indicator of the performance of digester (Mata-Alvarez, 2003).

The degradation of butyrate to acetate is not energetically feasible under standard conditions, but is dependent on co-culture with a hydrogen-removing organism. The degradation of acetate to methane is thermodynamically feasible where H_2 serves as the metabolic link between a non-methanogenic and a methanogenic bacterium as shown in chemical reaction below:

$$CH_3COO^- + 4H_2O \rightarrow 2\ HCO_3^- + 4H_2 + H^+ \qquad \Delta Go' = +104.6\ kJ$$

$$4H_2 + CH_3COO^- + H^+ \rightarrow CH_4 + 3H_2O \qquad \Delta Go' = -135.6.0\ kJ$$

An increased hydrogen level inhibits the degradation of propionic and butyric acids due to its effect upon the thermodynamics of reaction, and therefore, can inhibit acetoclastic methanogens. Microorganism involved here are, *Syntrophomonas wolfei, Sytrophobacter wolinii, Syntrophous buswelii, etc.*

3. Methanogenesis

Methanogenesis as the final stage of anaerobic digestion generate methane in two ways: by methanogenic archaea either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen to yield methane and water. The microorganism responsible for these conversions are strict anaerobes, called methanogens, and are identified in the literature as "methanogens" or "methane former". Only a limited number of compounds can act as substrates in methanogenesis, among these are formate, acetate, H_2/CO_2, and methanol. The most important methanogenic transformations in anaerobic digestion are the acetoclastic reaction and the reduction of carbon dioxide. It has been estimated from stoichiometric relations that about 70% of the methane is produced via the acetate pathway (Madigan et al., 2003). Very few known species can perform this acetoclastic methane production, whereas nearly all known methanogenic species are able to produce methane from H_2/CO_2. The hydrogen pathway is more energy yielding than the acetate pathway, and is normally not rate limiting. It is, however, of fundamental importance due to its ability to keep the hydrogen pressure low in the system. The hydrogen-consuming methanogens are among the fastest growing organisms in the anaerobic digestion process and the accumulation of hydrogen is only likely to occur, for example, during process overload or toxic inhibition of these microorganisms. The minimum doubling time for hydrogenotrophic methanogens has been estimated to be six hours, compared with 2.6 days for the slow-growing acetoclastic methanogens (Lester & Birkett, 1999). Hydrogen-utilizing methanogens have been found to be more resistant to environmental changes than acetoclastic methanogens. Thus, methanogenesis from acetate has been shown to be rate limiting in several cases of anaerobic treatment of easily hydrolysable waste. The methanogens can be classified into two group following two processes to produce methane. Acetoclastic methanogens utilize acetic acid to produce methane whereas hydrogen-utilizing methane bacteria convert H_2 and CO_2 to methane as in:

$$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^- + \text{energy}$$

$$4H_2 + HCO_3^- + H^+ \rightarrow CH_4 + 3H_2O + \text{energy}$$

Methanogens have very slow growth rates so they are usually considered as rate-limiting in the anaerobic organic waste treatment. Waste stabilization in anaerobic digestion is accomplished when methane and carbon dioxide are produced. However, the ultimate yield of biogas depends on the composition and biodegradability of the waste feedstock but its rate of production will depend on the population of bacteria and archaea, their growth conditions and the temperature of the system. Table 2.1 shows the taxonomy of methanogenic archaea and their substrates.

2.7.2 Rate limiting steps

1. Hydrolysis/ Liquefaction phase

The hydrolysis is considered to be the key step in the biodegradation of complex wastes (Mata-Alvarez, 2003). For solid substrate, hydrolysis is the most speed –limiting step in anaerobic digestion (Schieder et al., 2000). The rate of hydrolysis of a particular compound is determined by the adsorption of hydrolytic enzymes to the biodegradable surface sites (Veeken & Hammelers, 2000).The major part of OF-MSW was composed of lignocellulosic organic aside from the small amount of soluble compounds such as carbohydrates, lipids and proteins and these materials have different degree of hydrolysis. In the case of lignocellulosic complex materials, the degradation depends on the type of microorganisms involved and the environmental conditions. The effect of temperature is particularly important on the hydrolysis step. The hydrolysis rate of cellulose in thermophilic conditions is about five to six times higher than that observed in mesophilic conditions (Bouallagui et al., 2005). Interestingly, Veeken et al. (2003) reported that the accumulation of VFA reduces the hydrolysis rate of biowaste. The principal methanogenic reactions involved are given below (Chynoweth & Pullammanappali, 1996).

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

Acetate: $CH_3COOH \longrightarrow CH_4 + CO_2$

Formate: $4HCOOH \longrightarrow CH_4 + 3CO_2 + 2H_2O$

Methanol: $4CH_3OH \longrightarrow 3CH_4 + CO_2 + 2H_2O$

Carbon monoxide: $4CO + 2H_2 \longrightarrow CH_4 + 3H_2CO_3$

Trimethylamine: $4(CH_3)_3N + 6H2O \longrightarrow 9CH_4 + 3CO_2 + 4NH_3$

Dimethylamine: $2(CH_3)_2NH + 2H_2O \longrightarrow 3CH_4 + CO_2 + 2NH_3$

Monomethylamine: $4(CH_3)NH_2 + 2H_2O \longrightarrow 3CH_4 + CO_2 + 4NH_3$

Methyl mercaptans: $2(CH_3)_2S + 3H2O \longrightarrow 3CH_4 + CO_2 + H_2S$

Hydrolysis rate is directly related to the amount of available surface of the substrate. Particle size is the key factor for the hydrolysis process. The rate of hydrolysis of particulate organic matter is determined by increased absorption site for hydrolytic enzymes (Weekend & Hammerers, 2000). Therefore, one way of improving performance of digester is reduction in size of the particle. According to study by Veeken et al. (2000), hydrolysis rate of selected biowaste increases at high temperature but has no significant effect in biodegradability in mesophiic temperature range. However, Vieitez and Ghosh (1999) reported that fermentative reactions stopped at a VFA concentration of 13,000 mg/L accompanied by a low pH of 5.

2. Methane phase

Methanogenesis is the rate-limiting portion of the process because methanogens have much slower growth rate than acidogens. Besides, methanogens are very sensitive to change in environmental conditions such as temperature, pH, toxicity etc. Methane formation is necessary to neutralize the pH by converting volatile fatty acids. Ammonia inhibition occurs at ammonia concentration of 1500 mg/L which leads to increase in pH up to 8.5, which is toxic to methanogens (Mata-Alvarez, 2003).

Table 2.1:Taxonomy of methanogenic archaea and their substrate

Methanobacterium	H_2 +CO_2, formate
Methanothermobacter	H_2 +CO_2, formate
Methanobrevibacter	H_2 +CO_2, formate
Methanosphaera	Methanol,H2
Methanothermus	H_2 + CO_2
Methanococcus	H_2 + CO_2, formate
Methanothermococcus	H_2 + CO_2, formate, pyruvate + CO_2
Methanoplanus	H_2 + CO_2, formate
Methanoculleus	H_2 + CO_2, formate, alcohols
Methanocorpusculum	H_2 + CO_2, formate, alcohols
Methanospirillum	H_2 + CO_2, formate
Methanosarcina	Methanol, methylamine, acetate
Methanolobus	Methanol, methylamine
Methanococcoides	Methanol, methylamine
Methanohlophilus	Methanol, methylamine

Source: Madigan et al. (2003).

2.7.3 Process controlling factors

1. Nutrient requirement

One of the key elements in the stability of the anaerobic digestion is nutrient requirement of microorganism. Nutrient deficiencies may result into digester failure. Methanogens have a variety of mineral nutrient requirements of their growth (Kayhnian et al., 1995). Besides macronutrient (N, P), some micronutrients (K, Mg, Ca, Fe, Mn, Mo) are necessary for their growth. Teixeira et al. (2004) emphasized that the nutrient balances for nitrogen, phosphorus and potassium need to be determined, with identification of their concentrations in feeds. Nitrogen and Phosphorus are the major nutrients required for anaerobic digestion.

The relationship between the amount of carbon and nitrogen present in organic materials is expressed in terms of the Carbon/Nitrogen (C/N) ratio. A ratio of 25-30 is considered optimum for an anaerobic digester (Polprasert, 1996). High C/N ratio is an indication of rapid consumption of nitrogen by methanogens, and it results in lower gas production. A low C/N ratio causes ammonia accumulation, and, thus, increases the pH value; the value exceeding 8.5 is toxic to methanogens. Nutrients must be present in the substrate in correct ratio and concentrations. This can be achieved by co-digestion of feedstock (Kayhanian &

Rich, 1995). An average ratio COD/N/P of around 600/7/1 is usually recommended for a substrate to be anaerobically digested (Mata-Alvarez, 2003).

2. Temperature

Temperature affects the survival, the growth as well as the activities of microorganism. Based on range of temperature in which bacteria function best, they are classified as psychrophilic, mesophilic, and thermophilic. The mesophilic and thermophilic temperature ranges are 20-40°C and 50-65°C, with the optimum value of 37°C and 55°C, respectively. In general, higher temperatures results in higher metabolic activities within the critical limit (Angelidaki, 2002). The overall process kinetics doubles for every 10 degrees increase in operating temperature, up to the critical temperature of 60°C. Above the threshold value of 60°C, a rapid drop-off in microbial activities occur (Harmon et al., 1993). Microbial growth rate (μ) and temperature are related by the Arrhenius equation: $\mu = Ae{-}^{E / RT}$ where A is a constant, E represents activation energy, R is the gas constant and T is a temperature Therefore as temperature increases the microbial growth rate (μ) should increase.

Mata-Alvarez, (2003) presented a graphical illustration depicting the relationship between the temperature range with anaerobic digestion rate (Figure 2.4). A thermophilic temperature range reduces the required retention time. The microbial growth, digestion capacity and biogas production could be enhanced by thermophilic digestion, since the specific growth rate of thermophilic bacteria is higher than that of mesophilic bacteria (Kim & Speece, 2002b). Mace et al. (2000) noted that the thermophilic condition allows higher loading rate and more methane production than that of mesophilic condition. The thermophilic temperature offers improved yields and higher biogas production. Pavan et al. (2000) studied a two-phase digester on highly biodegradable OFMSW and identified that the increase of temperature in the hydrolytic phase up to thermophilic level apparently does not improve either yield or kinetic. Thus, unlike methanogens, non-methanogens are not very sensitive to temperature change. Increased destruction rate of organic acids and increased downfall of pathogen removal are also possible in thermophilic conditions. Thermophilic have been mostly suggested for energy production (Noone, 1990).

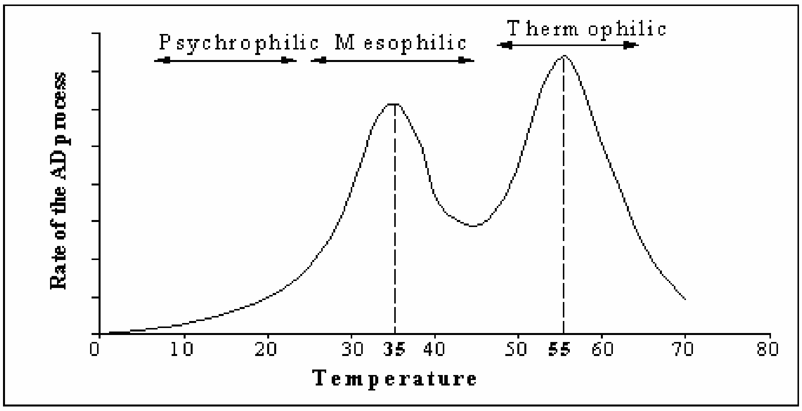


Figure 2.4: Temperature range for anaerobic digestion (Mata Alvarez, 2003)

3. pH value

In an anaerobic digestion, pH value plays a prominent role because microbial activities are influenced by it. In general, optimum growth of microorganism occurs within low range of pH values, from 6.7 to 7.5. Optimum pH values for acidogenesis and methanogenesis stages are different. Acidogens can tolerate the pH as low as 5.5 but methanogens are inhibited at such low value. During acidogenesis, large amount of organic acids are produced resulting into pH drop. The methanogens are very sensitive to pH, and will not thrive below a value of 6.5. The range of pH value that favors their growth lies between 6.4 and 7.2 (Chugh et al., 1999). Ammonia produced from degradation of protein provides the buffering to the system. However, if concentration of ammonia increases resulting into pH above 8, it becomes toxic. Though anaerobic digestion is satisfactory within the pH range of 6.8 to 7.2, the range of 7.0 to 7.2, shows the highest performance (Mace et al. 2000). Lien (2004) reported buffering effect of gravel, partly consisting of limestone, in the reactor bed. Zhang et al. (2005) mentioned the excellent performance of two phase anaerobic digestion with controlled pH at 7.

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

4. Feedstock characteristics

Biodegradability of municipal solid wastes differs from place to place to a great extent; its production and composition are influenced by climate, season, cultural practice, etc. In view of this variation, MSW characteristics as a feed stock play vital role in anaerobic digestion. The OFMSW has a high solids content (~50%), limited nitrogen content (C/N>30), and limited surface area available for degradation. Sorted municipal solid waste consists of 35- 50 % cellulose 20-35 % hemicelluloses and 15-25 % lignin. Food waste , for example, will lead to high biogas yields due to the high content of biodegradable organic matter but it can also lead to ammonia toxicity. Yard waste and newspaper, on the other hand, contain higher fractions of lignin and hemicellulose and will be characterized by lower biogas yield. The lignin and cellulose that are tightly complexed with lignin, are refractory to anaerobic metabolism. MSW constitutes typically of 40-50 % cellulose, 12 % hemicellulose, 10-15 % lignin and about 4 % of organics mainly proteins on a dry mass basis and that cellulose and hemicellulose constitute up to 91 % of methane potential (Vaidya, 2002).

5. Inhibitory and toxic substances

Biomethanogenesis is sensitive to several groups of inhibitors affecting the anaerobic digestion process; these are considered toxic or inhibitory at a given threshold level. VFA, pH, free ammonia, hydrogen and sulfur are the most frequent inhibitors. However, the toxic effect depends upon its concentration and the ability of the microorganism to acclimate its effects (Gerardi, 2003). Volatile acids such as acetate, butyrate and propionate cause alkalinity decrease and a drop in pH. The toxicity of NH_3 and VFAs is pH dependent since only the non-ionized forms exhibit microbial toxicity. However, acclimatization to toxicity and reversibility of the toxic effects are often observed. Some of the common toxic effects are given below.

A. Unionized volatile fatty acids

Acid accumulation plays an important role during start-up, and triggers process instabilities following shock loadings. At pH 6, five percent of the acetate present is in the protonated, or non-ionized, from, which is toxic to the bacteria. Protonated fatty acids can penetrate the lipid cell membrane. When they enter the cell, where a pH of 7 is maintained, they are ionized, and the released hydrogen ion will cause a decrease in the intercellular pH. According to Hanaki et al. (1994), propionic acid is believed to be the most toxic volatile fatty acid appearing in anaerobic digestion, and its oxidation to acetic acid is the slowest among all volatile organic acids (VFA). Veeken et al. (2000) reported a reduction of hydrolysis rate due to inhibition /accumulation of VFA. The accumulation of a specific fatty acid may indicate which step in the degradation chain is being inhibited or overloaded. But the accumulation of VFAs does not necessarily imply process failure. It has been claimed that the build-up of VFAs itself does not cause inhibition, but it is the combination with a fall in pH, leading to an increased amount of protonated VFAs, that causes inhibition (Kus & Wiesmann, 1995). Long-chain fatty acids have been found to be toxic to anaerobic cultures. The compounds are still degraded, but give an inhibitory effect on the methane formation. However, Angelidaki & Ahring (1992) investigated the effect of VFAs on process performance and observed no adaptation to the fatty-acid toxicity.

Table 2.2: Effect of ammonia nitrogen on anaerobic digestion

NH_4-N (mg/L)	Effect
50-200	Beneficial
200-1000	No adverse effect
1500-3000	Inhibitory at pH over 7.4-7.6
Above 3000	Toxic

Source: (Chynoweth and Pullammanappali, 1996)

Kim & Speece (2002a) presented three hypotheses explaining elevated VFA concentrations, specifically propionate. First, all phases of anaerobic digestion (hydrolysis, acidogenesis, acetogenesis and methanogenesis), if occurred in one vessel, would create an imbalance environment for VFA production and utilization rates because acetogens and methanogens have different metabolic characteristics. Second, Propionate is considered as one of the intermediate products in the metabolism of complex organics, and it degrades very slowly because consortia of three groups of bacteria are involved to convert it into acetate and hydrogen or formate. Propionate conversions to acetate and hydrogen and then hydrogen into methane are thermodynamically possible only at hydrogen concentrations in the range of 10^{-4} to 10^{-6} atmospheres. Third, all microorganisms need nutrients, but the limit of nutrient bio-availability can present operating problems including high VFA in the effluent. Microbial processes require enzymes activated by heavy metal ions.

B. Ammonical-nitrogen

Ammonical or ammonium ions prevail in anaerobic digester from degradation of organic nitrogen compounds (proteins), and exist in two forms, ammonium ion and free ammonia. Ammonium ions are nutrients for microorganism, but free ammonia is toxic to them, especially methanogens. Table 2.2 shows the effect of concentration of ammonium digestion in AD. The relative concentrations of dissolved ammonia and ionized ammonium are dictated by the system pH. At high pH values (>8) unionized form of N-ammonia dominates, and this form is more inhibitory than the ion. Free (unionized) ammonia can affect digester by inhibiting the enzyme which synthesizes methane or by causing into the cells and causing a proton imbalance (Kayhanian, 1999). However, dissolved ammonia and ionized ammonia are measured together and total amount is reported as the ammonia concentration responsible for inhibition (Mata-Alvarez et al., 2000).

Ammonia concentration greater than 1500 mg/L at high pH may result into digester failure (Gerardi, 2003). Vermeulen et al. (1993) reported a reduced biogas production rate with increased concentration of NH_4^+. For the dry fermentation of OFMSW at thermophilic condition, based on long term experimental studies, Kayhanian (1999) revealed that ammonia inhibition occurs at the concentration of 1200 mg/L. Much higher concentrations can be tolerated if the culture has undergone gradual adaptation, in anaerobic digestion of swine manure up to 1300 mg/L free ammonia has been shown to be tolerated without inhibition (Hansen et al., 1998).

The inhibition problem could be overcome either by the dilution of digester content or by adjusting feedstock C/N ratio (Mata-Alvarez, 2003). Methanogens being obligate anaerobic microbes, oxygen ions or alternate electron accepter like nitrate or sulfate ions are toxic to them. Oxidation-Reduction values of -300mV are required for proper activity of methanogens (Gerardi, 2003). Beside ammonia, other toxic substance also inhibits AD process. Some inhibitory substance with their concentration has been presented in Table 2.3.

Table 2.3: Concentration of inhibitors in anaerobic digestion

Inhibitor	Concentration (mg/L)
Aromatic compounds phenol[a]	 2400
Heavy metals[b] Zn^{+2} Fe^{+3} Cd^{+2} Cu^{+2} Cr^{+3} Cr^{+6} Nickel	 160 1750 180 170 450 530 250
Calcium[d]	2500-8000
Magnesium[d]	1000-3000
Potassium[d]	2500-12000
Sodium[d]	3500-8000
Sulphide[c]	600

Polprasert (1996) cited [a,c] Parkin et al. (1983),
[b] Mosy and Hughes (1975), [d] WPCF (1987)

6. Substrate loading rate and retention time

Organic loading rate is a measure of biological conversion capacity of anaerobic system, typically expressed as weight of organic matter (volatile solids or COD) per bed volume of reactor in a certain period of time. This parameter has a significant influence on the process performance. Sufficient loading rate could reduce the digester performance due to the lack of nutrients for microbial growth. Overloading can cause imbalance activities of methanogens and acidogens which may result into higher VFA concentration and less gas production. When VFA concentration increases, feedstock should be reduced. Retention time required in anaerobic digestion depends upon waste composition and characteristics, mode of operation, operating condition etc.

7. Reactor configuration

A non-mixed batch reactor offers significant benefit in relation to gas production and volatile solids (VS) removal. This was concluded by Kim& Speece (2002) who evaluated the process stability and efficiency of five different reactor configurations namely; batch-fed continuously stirred tank reactor, continuously-fed CSTR, 2-phase CSTR and non-mixed batch reactor. It was observed that during the start-up, non-mixed batch reactor exhibited stability in shorter period compared to the other systems, even with the increase in organic loading rate. The height of the reactor is another factor on the effect of maximum flow rate (Brummerler et al., 1992).

8. Inoculums

Performance of the anaerobic digestion is influenced by microbial diversity. It is, therefore, imperative that appropriate inoculums and its amount be selected for the degradation process to proceed (Angeldaki, 2002; Lopes, 2004). Brummerler et al. (1992) also reported that the higher the value of inoculation ratio (ratio of inoculum solid to total solids) the higher the digester performance.

2.8 Performance monitoring parameters

Process inhibitory parameters vary form substrate to substrate and for different environmental and operating condition. Most commonly used parameters are given below.

2.8.1 Specific gas and methane yields

Specific gas production or methane yield is directly related to the extent and rate of feed conversion, and, thus the anaerobic process efficiency. However, a low gas/methane yield should not be taken as an indication of deficient performance; it is simply a low biodegradation of substrate. The specific gas production and the ultimate methane yield both are expressed as m^3 CH_4/kg VS added. The methane content of gas is a good indicator of process stability. Under normal circumstances, methane content is a function of H/C ratio of biodegradable fraction and is normally in the range of 50-60% for MSW (Chynoweth et al., 1994). The biochemical methane potential (BMP) assay, that defines the maximum methane production during the 50 days under thermophilic condition, is useful for estimating the ultimate methane yield and relative conversion rate of feed samples, specific feed components and remaining biodegradable matter in the process residues (Hansen et al., 2004).

2.8.2 Volatile solids destruction

In addition to specific gas production and methane yields, the net change or loss in volatile matter is also a measure of biodegradation of the feed samples. It is more appropriate to use volatile solid loss rather than the total solid loss since the destruction is limited to organic matter. The efficient process will be the one in which, high volatile acid loss could be obtained in a way that the pollutant load in leachate would reduce and specific gas would increase.

2.8.3 Volatile Fatty Acid (VFA), pH and alkalinity

Organic acids, pH and alkalinity can influence digester performance. Measuring the alkalinity provides a picture of both how 'safe' the reactor is in relation to buffering acidic shock loads and of how healthy the reactor is, as it is normal for alkalinity to be between 1000 to 5000 mg/l as $CaCO_3$. Titration of sample to pH 5.75 results in a measure of the alkalinity due to bicarbonate; this is referred as Partial alkalinity (PA). Titration from 5.75 – 4.3 gives the alkalinity attributable to the volatile acid alkalinity, called Intermediate alkalinity (IA). The successful operation of a digester depends upon maintaining adequate bicarbonate buffering and the ratio of IA/PA between 0.1-0.3 gives an indication of system stability.

Under conditions of overloading and the presence of inhibitors, the microbial activity can not remove hydrogen and organic acids as fast as they are produced. This will result in significant increase in concentration of VFA, depletion of buffer and thus depression of pH. Significant increase in the concentration of VFA will occur before any significant decrease in pH is observed. Therefore, VFA can act as an early warning indicator of impending failure which can be corrected by external alkali (Lester and Birkett, 1999). If uncorrected, pH will drop to a level at which the fermentation stops. Three critical ranges of values were reported by Callaghana et al., 2002. Accordingly, a value < 0.4 indicates stable digester condition where as a value ≥ 0.8 indicates significant instability. The range of VFA (0.4–0.8) signifies that some instability will occur. A normal healthy volatile acid to alkalinity ratio is 0.1. An increase of this ratio to 0.5 indicates the onset of failure, and a ratio of 1.0 or greater is associated with total failure. The alkalinity needed to neutralize VFA is calculated by multiplying 0.833 times the VFA concentration (mg/L as acetic acid). Bolzonella et al. (2003) noted that the importance of parameters to be monitored for the process stability can be expressed as:

VFA concentration > alkalinity (at pH 4) > Gas Production Rate (GPR) >Methane content > Alkalinity (at pH 6) > pH.

Figure 2.5 shows changes in performance parameters (VFA, Alkalinity, and pH) during the onset of instability and failure of anaerobic digestion. At point A on the top of this figure (VFA/Alkalinity change curve), volatile acid has increased followed by decrease in alkalinity at point D as a result of which the digester has become sour at point G. In the similar manner, methane (CH_4) production begins to drop with a corresponding increase in CO_2 when VFA alkalinity ratio reaches 0.5. However, pH drop occurs only when the digester becomes sour.

2.8.4 Temperature

The anaerobic digestion process is due to the interaction and equilibrium of different microorganisms, and therefore, temperature stability is of particular importance. Different microorganisms have different optimum temperature range at which they thrive; the temperature ranges determine totally different microbial population rather than shift of original population. A variation of 2-3 ^{o}C in temperature can give rise to a change of the system.

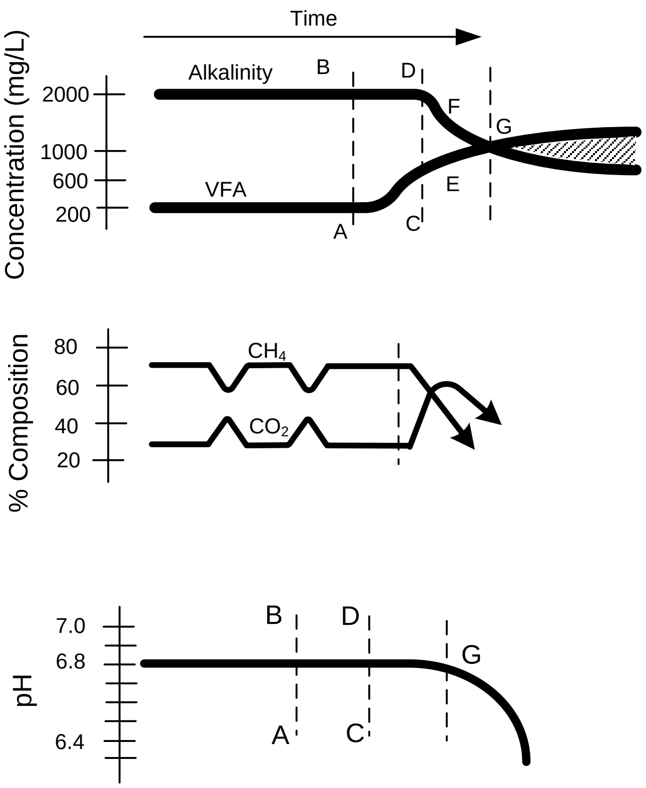


Figure 2.5: Changes in performance parameters (VFA, Alkalinity, and pH) during the onset of instability and failure of anaerobic digestion (Chynoweth and Pullammanappali, 1996)

2.9 Modes of operations of anaerobic digestion

2.9.1 Based on solid contents

Anaerobic digestion of solid waste can be classified into different categories based on solid content, feeding modes, stages of operations, operating temperature. Based on solid content of digestate, digester can be classified into:

- Low-solid anaerobic digestion with a dilute feedstock of less than 8%.
- Semi solid (semi liquid) anaerobic digestion with solid content of 7-15%.
- High-solid anaerobic digestion with solid content of 20-40%.

Conventional anaerobic digestion requires feed material with a total solid content below 10%. It has now been established that anaerobic biological treatment of biowaste is possible even with high solid content of solid material of about 45% (Mohee & Ramjeawon, 2003). Modern concepts accept total solids in the range of 20-80%.

Low solid (wet) digestion systems were established at the beginning of 1990 and have been popular mode of AD ever since. However, high solids (dry) digestion plants gained ground gradually from 1993 as results from research established that the dry systems have higher biogas yield (Verma, 2002). The high solid system has attracted much attention these days, to the extent that in 1998, more than 60% of digestion capacity was provided by dry fermentation system. Currently, no clear technology trend can be observed as the use of both systems is evenly distributed (Baere, 2000).

One of the major disadvantages of the low-solids anaerobic digestion process is that water must be added to bring the solid content lower than 10-15%, and thus, the diluted-digestate requires dewatering prior to the landfill. This results into large amount of wastewater and a smaller amount of compost. In dry process, only little water has to be added to dry matter content, consequently, the process does not requires costly dewatering of the fermented material. The compost from aerobic composting and dry fermentation consist of more inert material whereas the compost from wet fermentation has a higher VS content. The dry system is relatively simple in handling and secure in operation and cost effectiveness. A comparative study of a full-scale dry process and a wet process concluded that specific gas production of the two systems is practically identical (Luning et al., 2003).

Technically, high solids systems are more robust and have high organic loading rate but result into accumulation of volatile acid during the start-up.

Batch system being technically simple, less investment cost and more control over the process make it attractive for developing countries. However, necessity of close observation of safety measures during the opening and emptying of the batches to avoid explosive condition can not be ignored. According to O'keere et al. (1993), the limitations of the high-solids batch anaerobic composting is the requirement of heavy inoculum, mixing, and possibility of the instability and difficulty to overcome instability. To overcome inoculum addition, mixing and instability problems sequential batch system also known as SEBAC has been developed.

2.9.2 Based on operation process

Anaerobic digestion can be classified into two processes based on the stages of operation; namely batch and continuous process.

- Batch process: In this process, 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.
- Continuous process: In this process, the reactor vessel is fed continuously with digestate material. Fully degraded material is continuously removed form the bottom of the reactor.

The main difference between these two methods is that in the batch process, the steady state situation is never reached, whereas, in the continuous process, this is a pre-condition. Further, the batch process accumulates VFA and H_2 with time, which can change the process conditions (Mata-Alvarez, 2003). Although the land required for a batch processes is considerably larger, the system is technically simple and less capital intensive, small water consumption compared to the continuously fed systems (Brummeler, 1992). Clogging, need of bulking agent and risks of explosion during emptying of reactor are some disadvantages observed in the batch process.

2.9.3 Based on phase of operation

Based on the phase of operation, the anaerobic digestion process can be grouped into single-phase and multi-phase system. In general, the two-phase system provides rapid and stable treatment increasing the rate of hydrolysis and methanization (O'Keefe and Chynoweth, 2000). However, the claimed advantage of the two-phase digestion has not been substantiated in real practice (De Baere, 2000). Contrary to the claim, the added investment cost and operating complexity have caused this system to be limited in a small market share. Kim and Speece (2002a) concluded that two-phase digestion system showed little benefit over single-phase during start-up period and no benefit were observed during the long-term period. The high digestion rates provided by the single phase system makes the system a viable even today. Two phase system is suitable for protein enriched waste and one phase system for waste with C/N ratio15 (Mtz.-Viturtia et al., 1995).

2.9.4 Based on operating temperature

The optimum temperature required for digestion may vary depending up on the feedstock composition. In most anaerobic digestion processes temperature should be maintained relatively constant to sustain the gas production rate. Based on the operating temperature, an anaerobic process can be a mesophilic, if it operates in the temperature range of 20 to 40 ^oC, or a thermophilic, if it operates above 50 ^oC. Both mesophilic and thermophilic technologies are proven systems. Early digestion plants were mostly mesophilic. Thermophilic dry fermentation plants came into existence later and became attractive due to higher gas production and pathogen killed-off (Baere, 2000). Zupancic and Ros (2003) supported the argument that the thermophilic digesters are more efficient in terms of retention time, biogas production and digester capacity. Bouallagui et al. (2005) reported that biogas production from the experimental thermophilic digester was higher on an average than from psychrophilic and mesophilic digesters by 144 and 41%, respectively. There is an energy balance argument supporting the use of the energy produced to maintain thermophilic operating temperatures However, mesophilic plants are still in operation, and no clear trend has been observed. Despite its obvious benefits, thermophilic systems are expensive technologies enquiring greater energy input, and a higher degree of operation and monitoring. Ammonium toxicity can be in thermophilic condition due to higher ammonia solubility and to the displacement of ammonium- ammonia equilibrium towards the unionized form (Mtz-Viturtia et al., 1995).

2.10 Sequential batch anaerobic composting (SEBAC)

2.10.1 General description of SEBAC

The Sequential Batch Anaerobic Composting (SEBAC) process uses a combination of high solid fermentation and leachate recycling between new and mature reactor to provide moisture, nutrients and inocula for rapid start-up (Chynoweth et al., 1992). This process requires two reactors: a new reactor containing fresh waste and a mature reactor containing anaerobically stabilized waste. Leachate from the old reactor is re-circulated to the new reactor daily. The process is uniquely controlled by limiting volatile fatty acids concentration formed during the start-up. After pH of the leachate reaches 7 and biogas contains 50% methane, the new reactor is disconnected from mature reactor, and leachate from new reactor is re-circulated directly on itself. The old reactor is emptied to be ready for new cycle. This process is continued till the waste is degraded. Figure 2.6 represents the schematic of SEBAC process. The sequencing also refereed as stat-up period usually lasts for two weeks (Silvey et al., 2000). According to Juanga (2005), reactor, which is inoculated through matured leachate recirculation, reaches active methane phase earlier than reactor with seeding material and pH adjustment. Thus this process not only eliminates the need of inoculation but also shortens up the digestion time.

SEBAC process, being reliable and stable, can serve as a key element in the operation of sustainable integrated biodegradable solid waste management systems (Chynoweth et al. 2003). This process is of interest because of its inherent operational flexibility in terms of cycle time and sequence, and retention of a higher concentration of slow growing anaerobic bacteria within the reactor.

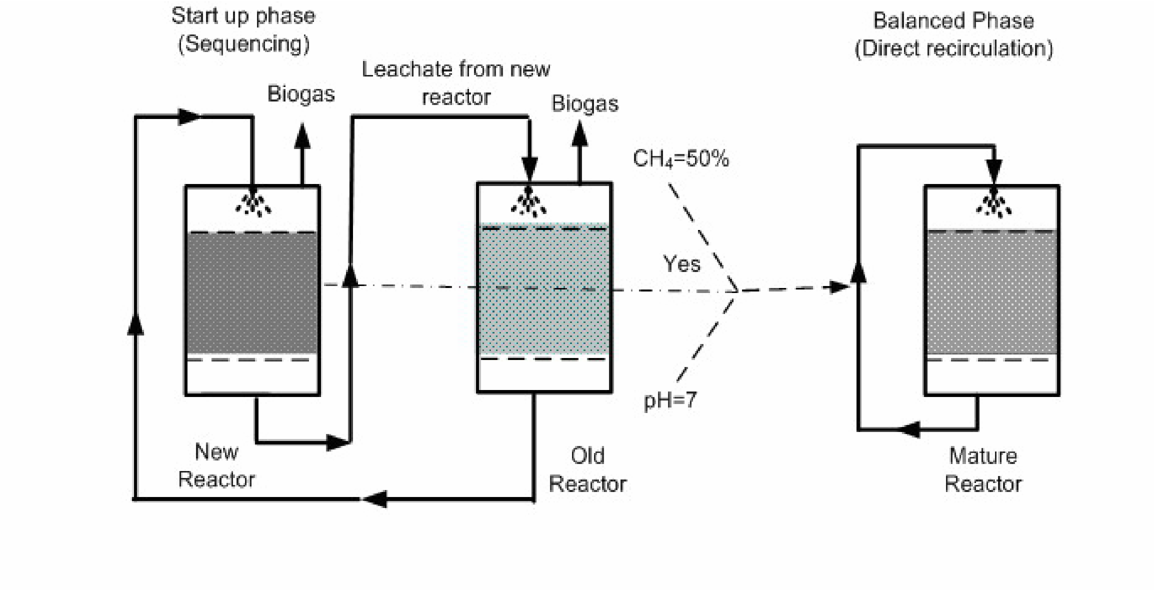


Figure 2.6: Schematic of Sequential Batch Anaerobic Composting (SEBAC)

2.10.2 Problems with Batch process

As explained in subsection 2.10.1, batch system digesters are filled once with fresh wastes with or without addition of seed materials, and allowed to go though all degradation process. The leachate collected in chambers is sprayed on top of the fermenting wastes. One technical shortcoming of such a process is that clogging can occur at the perforated floor (Brummeler, 2000). Although the batch systems are well suited to the demands of treating relatively large quantities of waste, however, biogas production is variable and the somewhat unsteady (Evans, 2001). Besides, the batch systems are technically simple; the land area required by the process is considerably large. Because of these shortcomings, batch system up to now has no been able to succeed in taking a substantial market (Bouallagui et al., 2005).

2.11 Continuous Anaerobic Digesters (CAD)

2.11.1 General description of CAD

Considerably large area requirement for the batch system has prompted the researchers to design a system that can take continuous feedstock in put (Mtz. Viturtia et al., 1995). The continuous input AD requires less land area and its operating cost can be comparable (Brummeler, 1992). Importantly, the higher initial investment cost may be compensated from real state cost reduction where the land is scarce. About 90% of the full scale plants operating in Europe are continuous one stage system (Bouallagui et al., 2005).

In a continuous digestion system, the input and removal of biowaste happens in an unbroken cycle. The system receives its weight little by little, spread over time, so that digestion takes place uninterrupted having no end point. However, a technical difficulty associated with pump has been encountered in loading the feedstock in continuous manner (Sharma et al. 2000). This has shifted the research focus on semi-continuous mode of operation. Semi-continuous digesters are fed at continuous intervals of time, as for example on daily basis, or on more frequent intervals, with simultaneous removal of the digestate (Wang et al., 2003; Misi & Forster, 2002). These systems are suited to regularly and steadily arising waste stream. The biogas yield of semi-continuous processes is characteristically higher and more regular. The higher production rate is attributed to the waste that is kept in their original state, and not diluted with water (Oleszkiewicz & Poggi-Varaldo, 1997).

The distinction between continuous and semi-continuous system is rather subjective. Most of the continuous digesters in large scales are not truly continuous. They are operated in semi-continuous mode (Sharma et al., 2000). The term ‘continuous system’ is used in a broader sense, which includes truly continuous and semi-continuous digestion systems where the digesters are feed once or twice a day.

2.11.2 Problems and Limitations of CAD

Because the continuous system has to cope with steadily arising waste, the digester vessels are relatively bigger than the batch digesters. Mixing is of pivotal importance in all AD systems, continuous systems rely on pumping for its continuous operation (Lissens et al, 2001). Further, the continuous system requires high internal fluidity for the smooth feedstock intake and removal process. Such systems are, therefore, principally suitable for low solid wastes. For higher solid content transport and handling of the waste carried out with conveyor belts, screws and powerful pumps especially designed for viscous streams. Such types of equipment are very expensive (Mata-Alvarez et al., 2003).

2.12 Biogas production/ application from MSW

The utilization of energy in the form of biogas is one of the environmentally sound alternative renewable energy sources. The organic waste produced by municipalities, industry and agriculture have a potential energy value that could ensure the economic viability of the process if fully utilized. OFMSW is very valuable substrate for biogasification with a biogas potential per ton of waste up to 10 times that of manure (Baraber, 1995). Further benefits include the reduction in waste volume and the production of a bio-fertilizer retaining all the nutrients of the original material.

Generally, organic fraction of municipal solid waste is a very attractive waste for the biogas plants because it has high yield potential. The AD potential of OFMSW may be classified on the volatile solid content and biodegradability. Consequently, methane yield from OFMSW can be classified into three groups, namely: hand sorted or source separated, mechanically separated and pre-composted. Methane yield from hand-sorted or source-separated was found to be 0.39- 0.43 m^3/ kg of VS. This value ranges from 0.18-0.26 m^3/ kg VS for mechanically sorted OFMSW and less than 0.14 m^3/ kg VS for pre-composted OFMSW (Gunaseelan, 1997). Rao et al. (2000) reported that biogas yield of municipal garbage was higher (0.564 m^3/ kg VS) compared to the cattle dung (0.252 m^3/ kg VS) and fruits and vegetable waste (0.429 m^3/ kg VS). Total biogas yield from municipal garbage was reported to be 2.5 times the yield obtained from cattle dung, indicating that AD of MSW is a suitable option for commercial energy production. Hartmann & Ahring (2005) estimated that 180-220 m^3 of biogas can be produced from one ton of OFMSW degradation. Bouallagui et al. (2005) reported biogas yield as high as 0.7 m^3/ kg VS from fruit and vegetable treated in a tubular digester.

2.13 Post treatment technologies

At the end of the anaerobic digestion of solid waste, there will be residual fibrous material which can be used in some way. This end-use may range from simple landfill cover, direct land spread to the production of high quality soil additive via some sort of secondary maturation process (Evans, 2001). In connection to the secondary maturation process, post treatment technologies have evolved. Common post treatment methodologies include dewatering, aeration and aerobic maturation. Various products may be recovered from dewatering and aerobic maturation. Whereas liquid fertilizer is derived from dewatering, post treatment of digestate results into marketable compost. The quality of the digestate is one of the most important issues affecting its use, along with prospective purchaser acceptance and economic considerations. The stabilized dewatered residue may be market as compost for use as soil conditioner or burned with power generation which appears to be the most economical long-term option and placed in a landfill. Final preparation of the residue will be influenced b the proposed end use of the product (Jonathan et al., 1995).

The importance of a good feedstock cannot be overstated if the digested material is to have a real final value. Thus source separated waste has advantages over the mixed MSW. Figure 2.8 shows the total recycle process for MSW. Anaerobic digestion does not reduce nitrogen, phosphorus and potash content but keeps the value of nutrients intact for fertilizer (Ostreme, 2004, cited Mahony et al., 2002). Anaerobic digestion of MSW putrescible could solublise around 50% of the nitrogen. Thus, the anaerobic digestion of putrescible may become an important method of increasing the rate of nitrogen recycling back to the ecosystem (Jokela & Rintala, 2003).

2.13.2 Dewatering

Post treatment process commonly includes dewatering, aeration, and leachate treatment. When digestion is complete, the digestate or the residue is removed. The greatest energy use occurs in dewatering of anaerobic digestion residue; water content must be reduced to 55-60% in order to achieve optimum moisture conditions for post-decomposition. Dewatering is done by using screw presses, wire presses, centrifuges, decanters and cyclones (Fricke et al. 2005). The water content in the residue is drained off through filter press, or belt press and recirculated to the digester. The filtered cake is cured aerobically, usually in compost piles, to make compost. Though, water obtained from dewatering can be used as liquid fertilizer, logistics of transporting high quantities of water make it uneconomical. The quantity of surplus water depends upon the substrate properties and digestion technology involved; the quality of compost depends upon the waste composition. In addition to the possibility of liquid fertilizer extraction from the liquid phase, VFA would also be extracted and converted to products like methyl or ethyl esters, for commercial purposes (Mata-Alvarez & Sans, 1995).

The main aspects of the compost quality are plant nutritional values i.e. inorganic nutrient as well as content of organic compounds, content of undesired goods, content of toxic compounds such as heavy metal or absorbable organic halide (AOX), and good hygienic stabilization (absence of pathogens). Among these aspects, first three are strongly related to input quality. If organic fraction comes in contact with grey waste fraction, toxic substances may be mobilized by pH variations contaminating the input. Therefore, if possible, digestion of only source-separated organic fraction of solid waste is recommended.

From environmental considerations, methane emission from post-treatment of anaerobic digestion plays an important role. The digestate material is saturated with anaerobic microorganisms and anaerobic digestion may continue to go causing methane emissions. Therefore, it is important to avoid the storage in heaps after extraction from digester; interruption as quickly as possible is necessary. Use of bulking materials such as wood chips and branches to loosen the compact structure of digestate allows better and quicker access to air. Inoculation of the active aerobic compost may help in quicker change in composition of microbial populations (Mata-Alverez, 2003).

2.13.3 Composting

There are certain advantages of post aerobic process of digester residue. Post treatment of digestate is an aerobic process which is also known as curing. One advantage is oxidation of reduced residue (ammonia, sulfides, organic acids), and the other is the reduction in pathogen killed off. Rao et al. (2000) demonstrated that because of the low C/N ratio (9.6), it can be utilized as soil conditioner. Technologies for composting can broadly be classified as agitated and static methods. In the agitated technique, the material to be composted is agitated periodically to allow oxygen, whereas in static method the composting material remains static and air is blown through the material. The windrow is widely used agitated method, and aerated static pile is one of the most common static methods available. On comparative study on windrow and static piles shows that windrow stabilizes rapidly than static piles (Gunasekera, et al., 2004).

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

Aerated static pile method requires the composting mixture to be placed in piles that are mechanically aerated using networks of pipes fitted with blowers. Air is introduced to provide oxygen needed for biological conversion, and to control the temperature with in the pile. The material is composted for three to four weeks, and cured for four or more weeks. Bulking agent may be used to absorb water, if required. However, dry materials like MSW or yard waste or mixture may not need bulking agents.

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

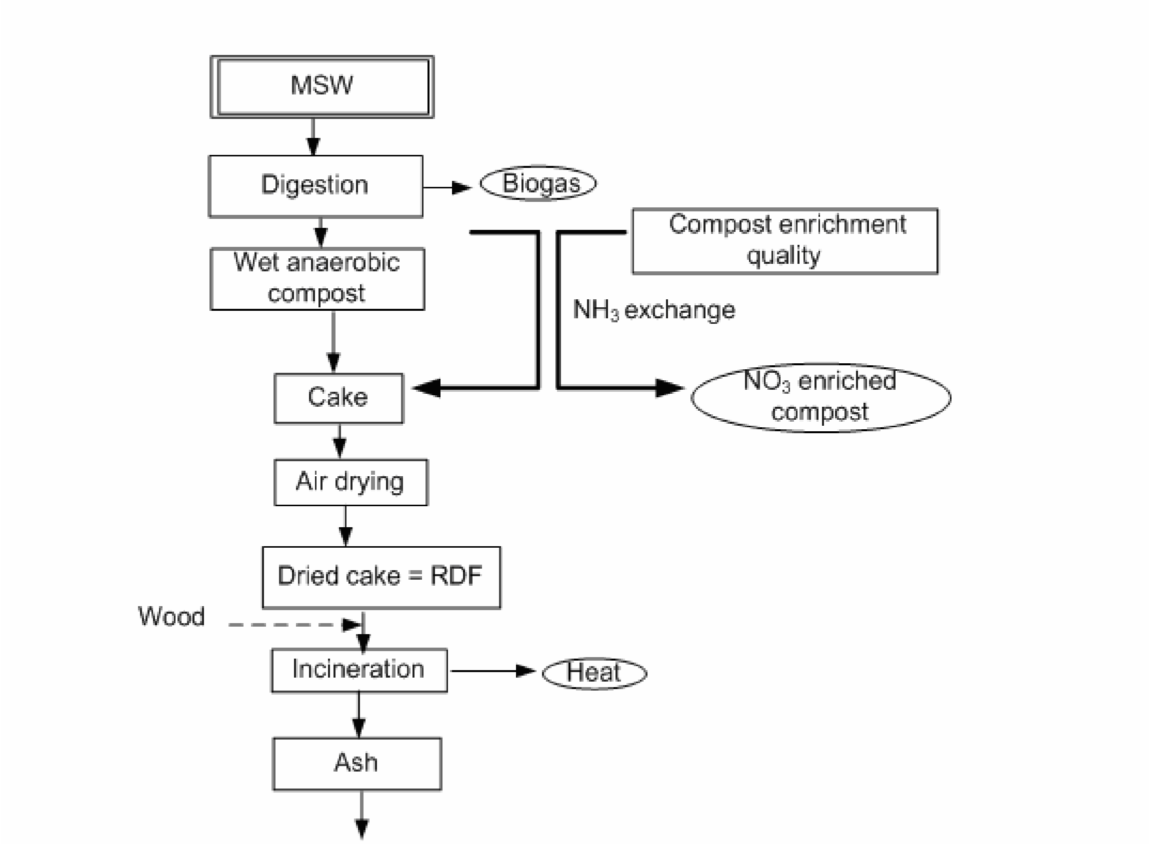


Figure 2.7: Overview of total recycle process of OFMSW (Lissens et al., 2001)

Chapter 3

Methodology

3.1 Introduction

Organic fraction of municipal solid waste can be digested anaerobically in low, medium and high solid content. It can be operated into batch and continuous mode. Each mode of operation has its own relative merits and demerits. This research involved both sequential batch and continuous anaerobic digestion of organic fraction of municipal solid waste collected from Taklong municipality dumpsite.

Experiments were conducted in pilot-scale reactors. Two pilot-scale reactors, designed for high solid fermentation were used to conduct sequential batch operation. These reactors were designed and operated by previous researchers (Lien, 2004; Juanga 2005). One of such reactors was modified to accommodate continuous feeding and withdrawal operation. Sequential batch operation has been operated for three complete cycles. Continuous reactor has been under investigation for five months with variable feeding rate.

Operating conditions such as flushing and micro-aeration recommended by Lien (2004) and Juanga (2005) was followed to start-up the digestion in this research. Completion of digestion was noted by exhausted biogas production in the reactor. The matured reactor was used to start-up a freshly loaded new reactor on many cycles of sequential operation. The sequential batch operation was conducted under thermophilic condition for 3 cycles. The sequential concept was being employed to shorten the anaerobic digestion period, with different rate (volume) of the leachate circulation in each cycle.

Laboratory scale Biochemical Methane potential assay was conducted to monitor relative anaerobic biodegradability of substrates, and to evaluate potential digestion process efficiency. Results obtained from both mode of operation have been compared in terms of biogas production and digestate waste properties.

3.2 Pilot scale experiments on batch process

3.2.1 Reactor design and configuration

Two parallel reactors, made up of stainless steel, were used for this experiment; digester design is illustrated in Figure 3.1 with dimensions. The total volume of the reactor was approximately 375 L while the designated volume available for the waste compaction was 260 L. The remaining volume of 45 L and 70 L on the upper and lower part of the reactor served as the available space for the generation of biogas and gravel support, respectively. The reactor was equipped with thermocouple sensor (T-type) inserted into the biowaste bed to monitor or control the temperature. Loaded substrate was compacted in the digester between two perforated plate in order to ensure a uniform distribution of flushed air or water to flow through or percolate into the system. The bottom part of the reactor had gravel, and waste was separated from the gravel by perforated plate. The upper 15 cm of the reactor was designed to provide allowable space for the installation of sprayer or sprinkler in order to distribute liquid uniformly.

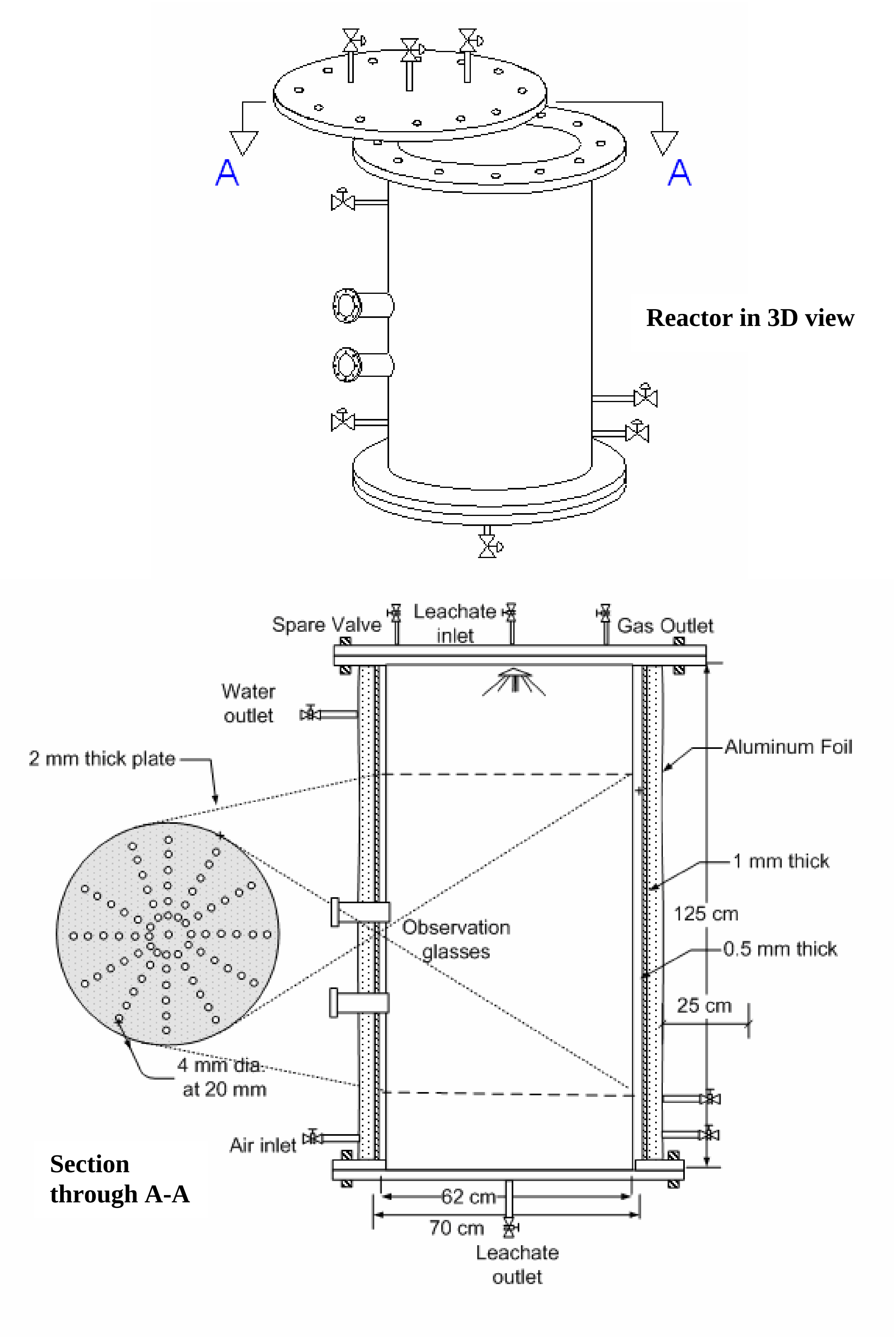


Figure 3.1: Pilot scale reactor design for anaerobic digestion

Besides pilot reactors, anaerobic digestion system consists of other equipment such as leachate tanks, leachate pumps, and air compressor to pump the air into the waste bed and provide a microaerophilic condition (low oxygen concentration). Figure 3.2 shows the sequential batch anaerobic digestion system in details.

3.2.2 Feedstock preparation

Solid waste was collected from Taklong municipality dumpsite. Only the organic fraction of waste (OFMSW) was taken for feedstock. Non-biodegradable fraction of waste such as plastics, tin cans, bulky and inert materials was separated by manual segregation that could otherwise hamper the digestion process. Since dumpsite receives solid waste from municipality as well as from a big fruit and vegetable market, vegetable refuse pre-dominates the waste compositions. Thorough mixing of collected waste was required to ensure homogeneity. After segregation, sorted waste was shredded down to a particle size of approximately 10 mm using a shredder. It is noted here that the size reduction would enhance the hydrolysis by providing larger surface area.

Clogging of perforated plate at the bottom of the reactor is one of the major issues in batch operation (Brummeler, 2000). To overcome this problem, Bamboo cutlets (2-3cm in diameter and 4-6 cm in length) were used as bulking agents to provide void space and facilitate the flow of leachate and gas. Bulking material also helps reduce the local clogging during flushing and cross circulation. In addition, the bulking material allows the biogas to escape easily from the waste bed during methanogenesis stage.

3.2.3 Run 1: Reactor stabilization

The objective of this run is to stabilize reactor to be used for SEBAC. Organic fraction of municipal solid waste was loaded into the reactor with compaction density of 600 kg/m^3 together with bulking agent (bamboo cutlets). The waste and the bulking material were mixed together before feeding to the reactor. Once the system matured, the percentage of methane in biogas reached 50, mesophiic condition (37°C) was shifted to thermophilic condition (55°C) by gradually increasing the temperature at the rate of 2°C per day. The process was deemed necessary to avoid unbalanced situation resulting from sudden temperature change as reported by Cecchi (2003). The gradual increase in temperature reduces stress situation without affecting the gas production. The process behavior in transient condition was investigated and subsequent experiments were carried out in thermophilic condition.

1. Pre-stage operation (leaching and acidification)

As described in previous chapter (section 2.7), bio-methanization of organic waste takes place in two steps, namely: pre-stage that involves liquefaction and acidification and main stage that consists of methane production. The strategy used to start-up the first reactor was a combined process with microaeration and flushing because of the benefits of microaerophilic condition and flushing reported in previous experiments (Lien, 2004; Juanga, 2005). Microaeration enhances oxidation of organics and leads to the higher degradation rate. Flushing was employed to wash-out the dissolved organic compound that would otherwise lead to the VFA accumulation and pH drop in the system. Flushing followed by microaeration could wash out soluble organics reducing organic load of the system. Flushing was started with 180L of water. Flushing was done for 4h run/ 4h stop(5L/ min) Microaeration was done at 1L/h for 2h during 4h stop of flushing. 180 L of water is replaced in day 2 and flushing and microaeration was continued for 3 days. Three days of flushing and microaeration was sufficient to reduce the load as recommended by Juanga (2005).

pH of the system was 5.6 after 3 days of pre-stage operation. As pH range for methanogenesis is 6.5- 7.3, pH of the system was adjusted to 7.0 using commercial grade NaOH. Overall procedure has been represented in Figure3.2.

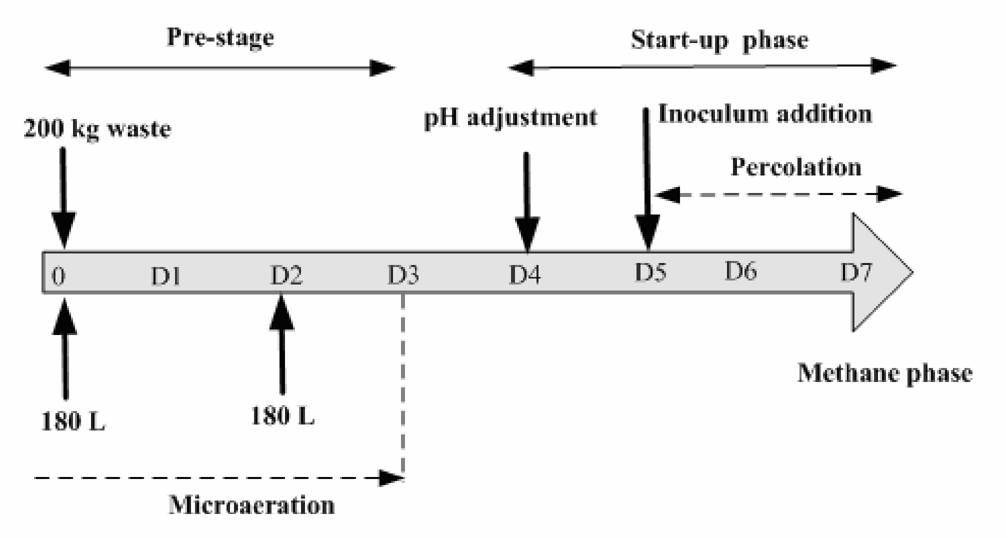


Figure 3.2: Procedural representation of start-up of first reactor

Moreover, periodic water replacement could help reduce the VFA level. The duration for pre-stage operation was 3 days as recommended by Juanga (2005).

2. Main stage operation

For the early commencement of methanogenesis, inoculum was added in the feedstock after pH adjustment. In day 5, 20 kg of inoculum (10% waste) was added. Seeding material (inoculum) consisted cow dung (8kg), digested waste (6kg) and anaerobic sludge (6 L). Anaerobic sludge was collected form anaerobic wastewater treatment plant form Singh Beer factory and cow dung from a cow farm located in Pathumthani province of Thailand. Digested waste was taken form previous experiments (Juanga, 2005).The inoculum was placed as a thin layer at the top of the feed stock, and distribution through out the waste bed was accomplished by percolation at the rate 200 ml/min for 4 hours runs per 4 hours stop for two days. The digestion was left undisturbed and biogas production and composition was monitored daily. Composition of methane (>50%) in the biogas was taken as an indicator of the phase maturity. Once the digestion process was active as indicated by pH 7 and 50% methane content in biogas, the operating temperature was gradually shifted

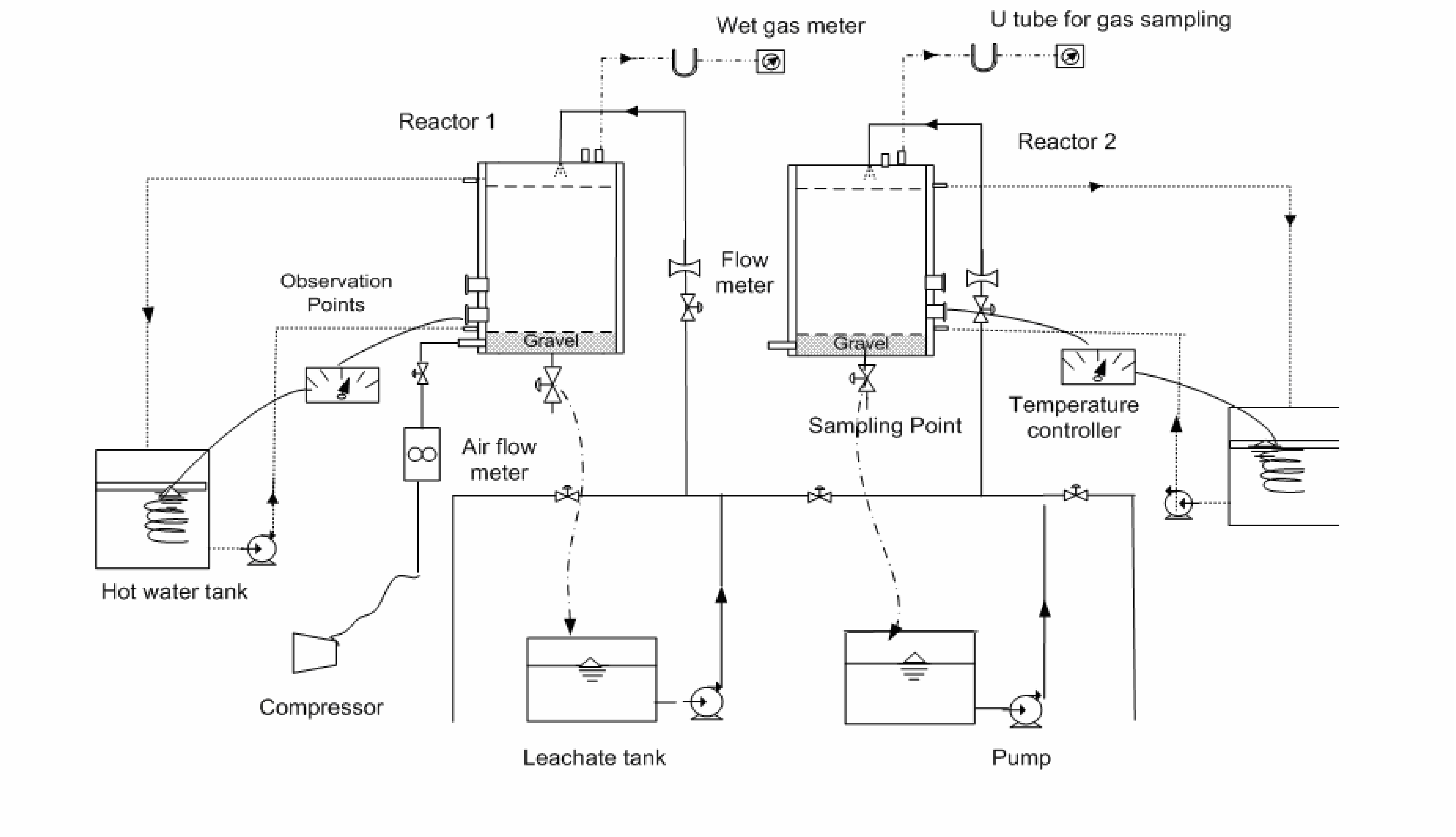


Figure 3.3: Sequential anaerobic digestion system

to thermophilic condition. The transient behavior was investigated. After the biogas production was observed so low (practically zero) under thermophilic condition, that the process was considered to have ceased. This reactor was used as stabilized reactor to start up the sequential operation.

3.2.4 Commencement of sequential operation: Cycle 1

The substrate was loaded into the new reactor (R2) after pretreatment (segregation and size reduction). The size of the substrate used was 30 mm. Mature leachate from old reactor (R1) was circulated to the reactor filled with fresh waste. The fresh waste bed was flushed with 90 L mature leachate from old reactor. Leachate from newly loaded reactor was circulated into the old reactor. The cross-circulation rate in this cycle was 3 L/min for 30 minutes. The pH of the leachate from new reactor and the biogas composition were monitored daily. Once the pH reached 7 and methane composition reached 50%, the reactor was assumed to have matured. Old and new Reactors (R1 and R2) were then uncoupled. The new reactor (R2) was now operating on its own with direct recirculation of its own mature leachate, independent from the old reactor. Figure 3.4 illustrates procedural representation of start-up and mature leachate utilization.

After the mature reactor became stabilized old reactor, it was used as an old reactor for starting up the cycle 2. A stabilized waste is defined as the waste that had been taken through its various stages of anaerobic digestion and exhausted of its methane producing potential (Chugh et al., 1999). Similar procedure was followed to start up the new cycle by coupling the mature reactor to the freshly fed-reactor. Figure 3.5 shows the schematic representation of operation. Aeration was applied on old reactor for safe unloading of the digestate. The sequential operation was continued for three cycles as depicted in Table3.1.

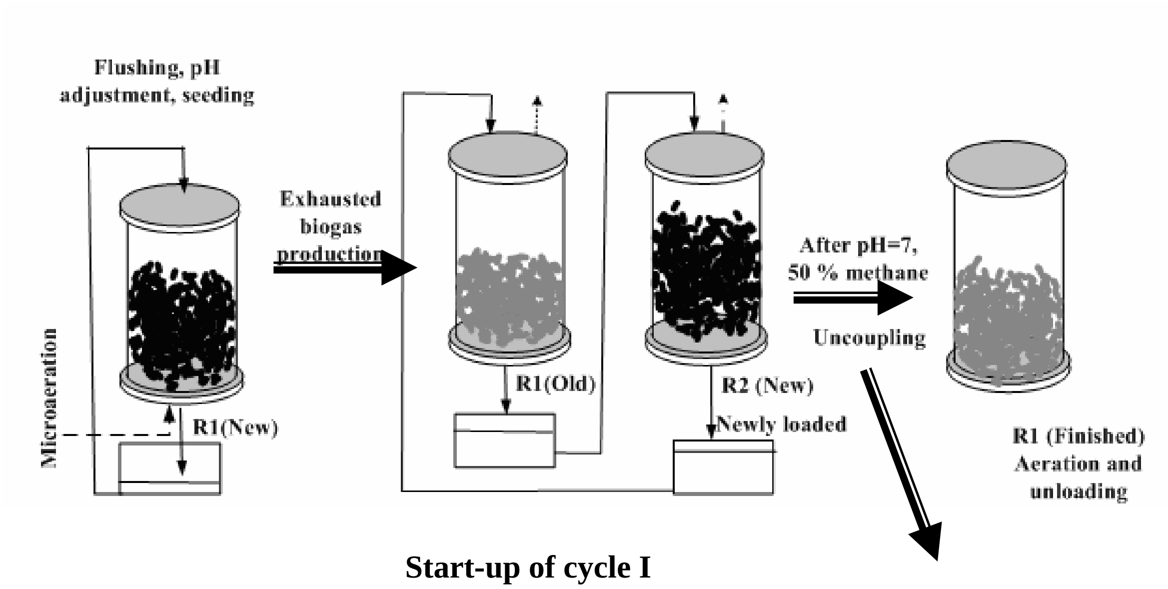
Table 3.1: Cross circulation rates in different SEBAC cycles

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

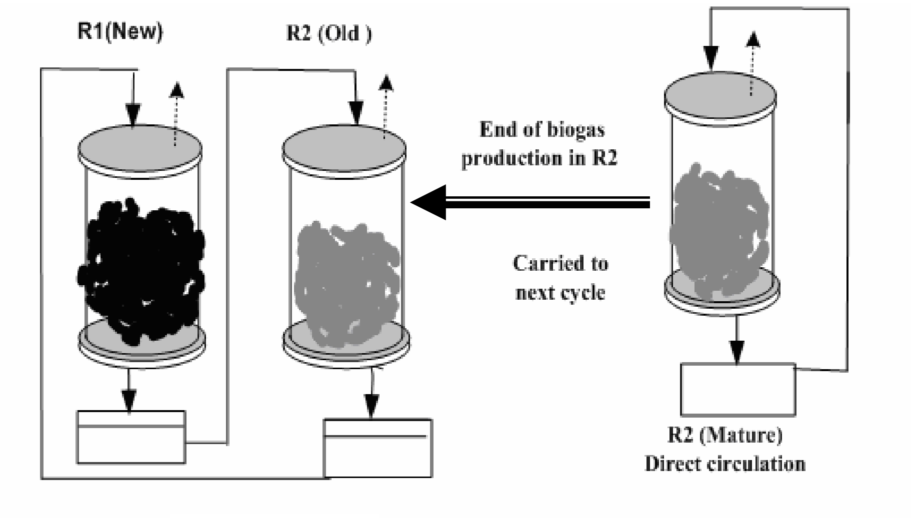
3.3 Pilot scale Continuous operation

3.3.1 Feedstock characteristics

For the continuous anaerobic digestion, solid waste was collected from Taklong municipality dumpsite. The waste was shredded down to average particle size of 10 mm. Enough feedstock was prepared to last for at least two weeks and stored in a controlled environment at a temperature of 4°C. The frozen waste was thawed to room temperature for 2-3 hours before feeding to the reactor to avoid temperature shock to the microorganism.



Start-up of cycle I



Cycle II

Figure 3.4: Representation of start-up and mature leachate utilization in process

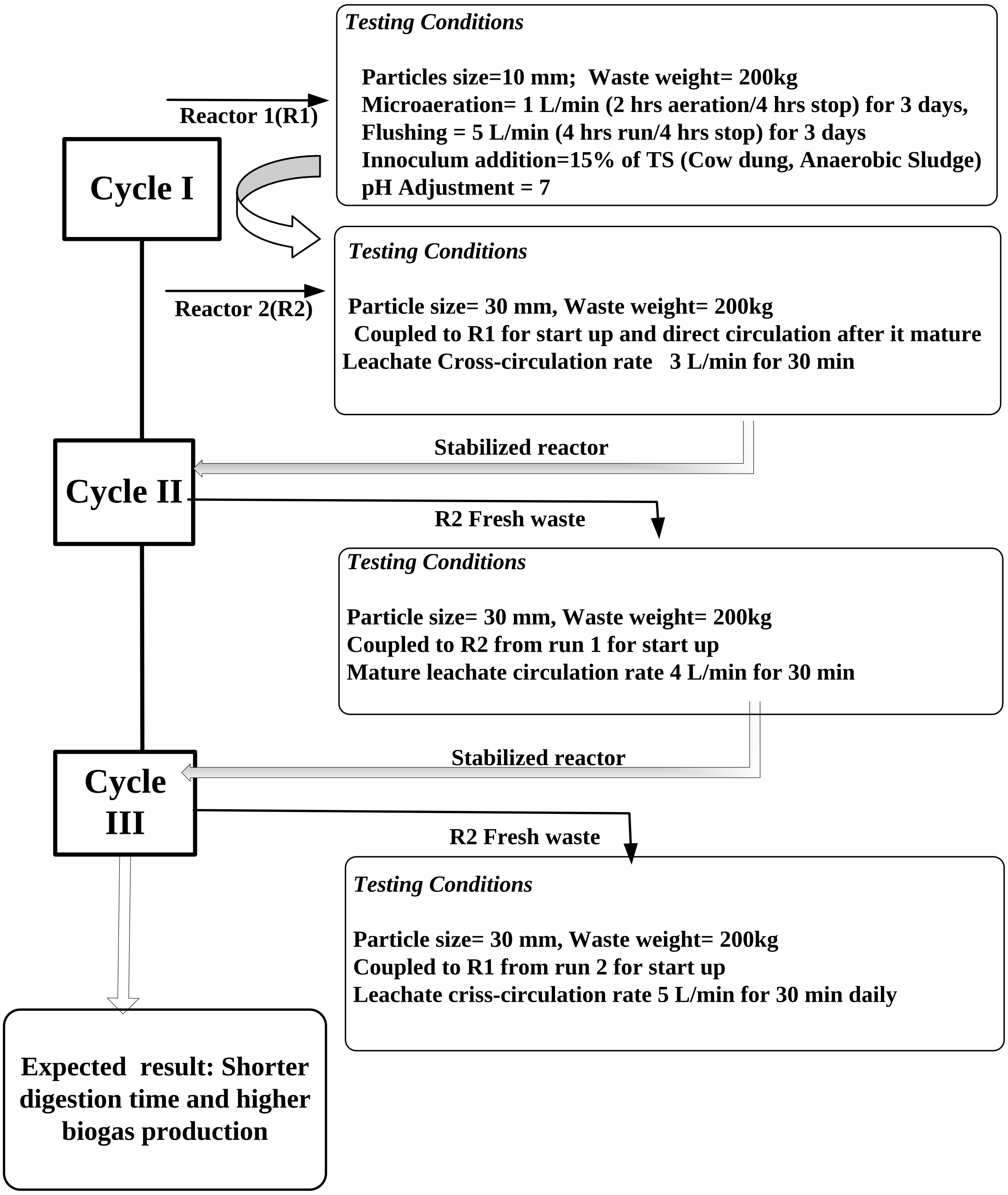


Figure 3.5: Overall schematic representation of sequential batch operation

3.3.2 Reactor design for continuous operation

A pilot scale digester previously used for batch process was modified so that continuous feeding and withdrawal was possible. The modified reactor for the continuous operation is illustrated in Figure 3.6 which has 240 L working volume. A container with 10 liter volume capacity was annexed to the top detachable cover with the regulator. The for feedstock supply at the top, and a chute for digestate collection at the bottom facilitate the input-output process. For the start-up of the operation, leachate was collected from collection point and circulated to provide mixing up of the feed.

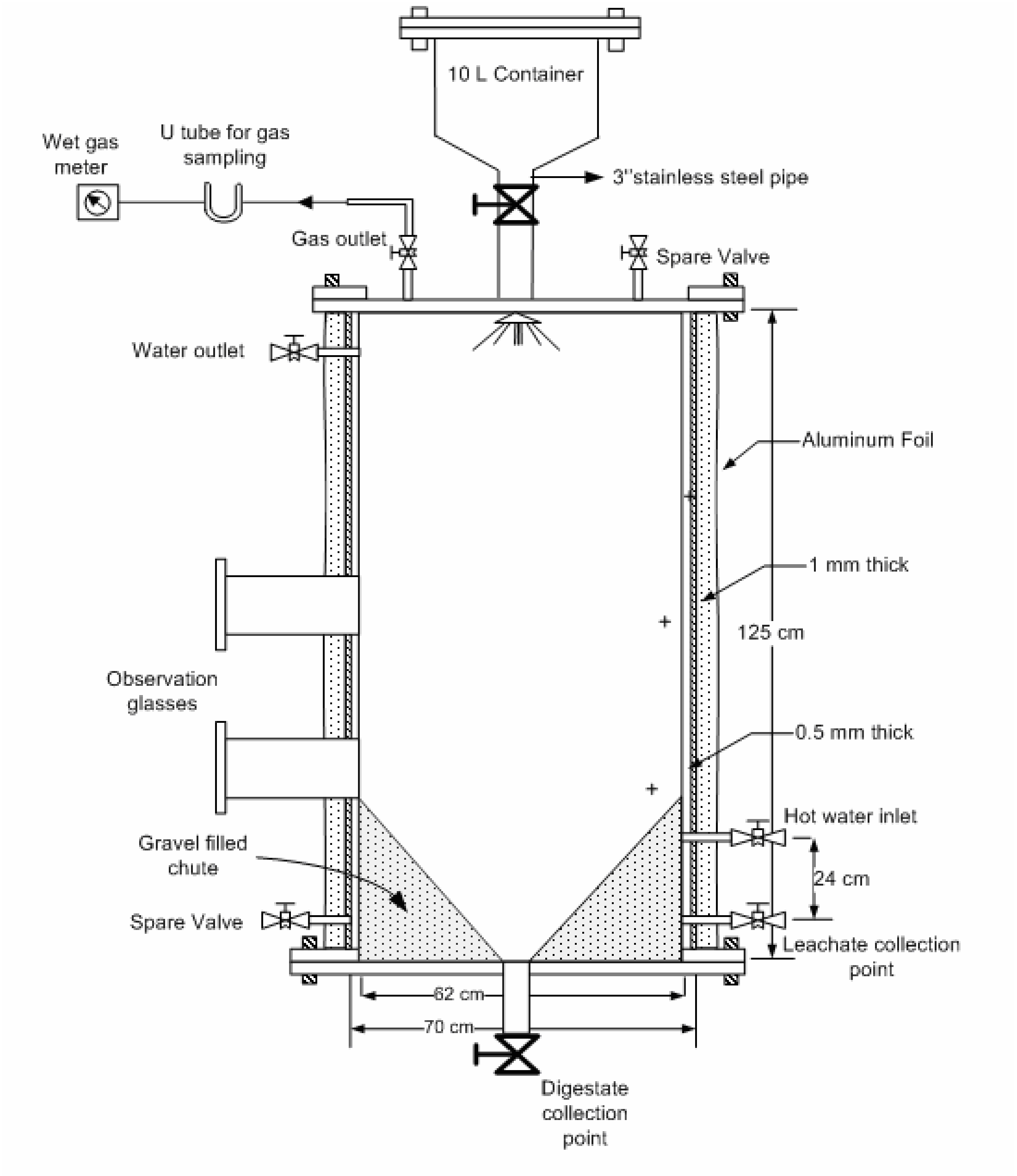


Figure 3.6: Continuous operation reactor design

3.3.3 Experimental procedural

a) Acclimatization of inoculum

Since the reactor was operated at thermophilic condition (55°C), the inoculum/seeding material was acclimatized first to thermophilic condition in a separate acclimatization set-up by increasing the temperature from 37°C gradually until it reached to 55°C. The inoculum contained 8 kg of cow dung, 6 kg of anaerobic sludge and 6 L of water. It is noted that the inoculum was acclimatized in 55°C for 4 weeks. Only when acclimatized inoculum produced negligible biogas, was it mixed with the substrate to start the digestion process.

b) First phase: Start –up of digestion

For the start-up of the digestion process, the digester was fed with 90 kg feed, to which 20 L of acclimatized inoculum (8 kg cow dung, 6 kg of anaerobic sludge and 6 L of water) was added. At this stage, the total feed intake was 50% of the reactor volume. Mixing is important in anaerobic digestion to ensure that conditions are consistent throughout the digester, and bacteria have rapid access to digestible surfaces. Mixing in the reactor in this experiment was carried out through leachate percolation at the rate of 200 mL/ min for 3 hours daily. Performance parameters like pH, alkalinity, VFA, biogas production and composition, etc. were monitored everyday.

c) Second phase: Batch feeding

No feed was applied to the digester for the two weeks as biogas production was increasing. Only when a drop in biogas production was observed, feedings were resumed at the rate of 3 kg of solid/day until it reached the full working capacity (80% of the digester volume).

d) Final phase: Continuous feeding and withdrawal

In a continuous operation, fresh material continuously enters the digester and equal amount of digested material is removed. During the final phase, leachate collected at the withdrawal was mixed with the fresh waste and fed through the container at the top. This would not only facilitate the loading by diluting the waste, but also allow mixing in the digester.

The reactor was initially fed with substrate at a small loading rate of 3 kg/day in a draw-and-fill mode. Prior to feeding, an equivalent amount of digestate was removed based on mass balance study. Daily feedstock input and withdrawal in each loadings is presented in Appendix E (Table E-2). The loading rate was increased at a predefined rate as explained in Table 3.2 as the experiment progressed. Mass retention time as defined by the waste in digester (in kg) divided by the daily feeding rate (kg), was used to determine the digestion period for each loading rate. Four such loading rates could be completed during the limited availability of research time. The working volume of the digester was approximately maintained at 80 % of the total digester volume. The mass balance was done using simple concept that for a balanced system, what goes in must come out. Details on mass balance are described in following section.

Table 3.2: Loading scheme for continuous operation

Feeding	Wet weight input per day (kg)	Mass retention time(day)	Loading Rate (kgVS/m3.day)
1	5	32	1.9
2	7	22	2.7
3	9	18	3.5
4	11	12	4.2

e) Mass balance analysis

The waste is a multiphase system consisting of solid and liquid phases. Whereas moisture in the waste is converted into leachate, solid mass reduction contributes to the biogas production. Figure 3.7 illustrates the simple material balance in digestion process. Mass balance analysis, therefore, must take into account the volume and composition of biogas produced. Biogas as produced contains methane, carbon dioxide, and water vapor and trace amounts of other gases. From a volumetric point of view, the trace gases are neglected; only methane and carbon dioxide were considered. The biogas mass is calculated using the molecular weights of methane and carbon dioxide (16 and 44 g/mol, respectively), the molar volume of an ideal gas at Standard Temperature and Pressure (STP) is 22.413 L/mol and normalized individual gas contents (vol. %) is estimated as:

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

Where G_m is the mass of biogas (g), V is the biogas volume at STP (l), CH_4 is the normalized methane content (vol. %), and CO_2, the normalized carbon dioxide content (vol. %). The following assumptions are made for the mass balance:

- The waste is fully saturated and consists of solid and liquid fractions only. Accordingly, theory of mixture can be used to describe the system.
- The loss of solid mass due to exothermic reaction in the digester that is the loss of mass due to thermal energy conversion is assumed negligible.
- The mass consumption by microbial growth is neglected as the yield coefficient is low for anaerobic microbes.

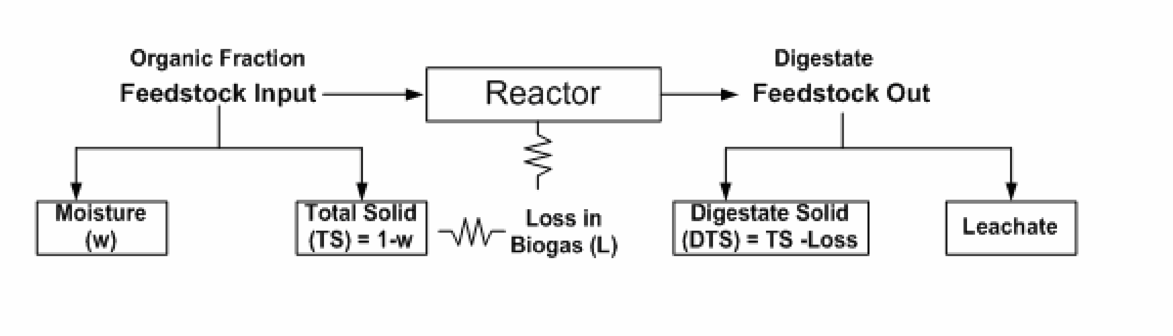


Figure 3.7: Material balance in continuous digestion process

Feedstock Intake

Assuming solid waste to be a solid-liquid phase system, total solid content and moisture content of the feed intake can be expressed as fractions of bulk weight as:

Total feedstock bulk weight (kg) = X
Moisture content (%) = w
Total moisture in a given weight of waste = $w \times X$
Total dry solid present in the waste (TS) = $(1 - w) \times X$

Total feedstock intake $X = (w \times X) + [(1-w) \times X]$ ………………………………. Eq. 3.2

Feedstock Withdrawal

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

Total bulk digestate withdrawn (kg) = Y
Total Moisture content = $w \times X$
Solid in Leachate (g/L) = S_L
Moisture content of digestate (%) = w_1

Water Mass Balance

Based on the mass conservation, the total water entering the system must be equal to the water leaving the reactor. If total Leachate leaving the digester is L and Total Moisture in digestate is ($w_1 \times Y$), water mass balance equation takes the form of:

Total liquid intake = Total liquid out

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

$\therefore$ Total leachate to be wihdrawn $= L = (w \times X) - (w_1 \times Y)$ …………………………. Eq. 3.3

Solid Mass Balance

It is noted that leachate withdrawn has dissolved solid given by $[S_L(w \times X)]$. Further, some solid is lost in 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:

Dry solid intake = Dry solid out

$$(1-w) \times X = S_L(w \times X) + \{V \times [(CH_4/100) + 44 \times CO_2/100)]/22.413\} + y \quad \text{……. Eq. 3.4}$$

Total digestate to be withdrawn (kg) $Y = \dfrac{y}{(1-w_1)}$ ……………………………. Eq. 3.5

3.4 Laboratory Analysis

3.4.1 Biochemical methane potential assay

Biochemical Methane Potential (BMP) can be used as valuable tool to monitor relative anaerobic biodegradability of substrates, and evaluating potential digestion process efficiency. Figure 3.8 shows the procedures of this assay. Procedural details can be found in Hansen et al. (2004).

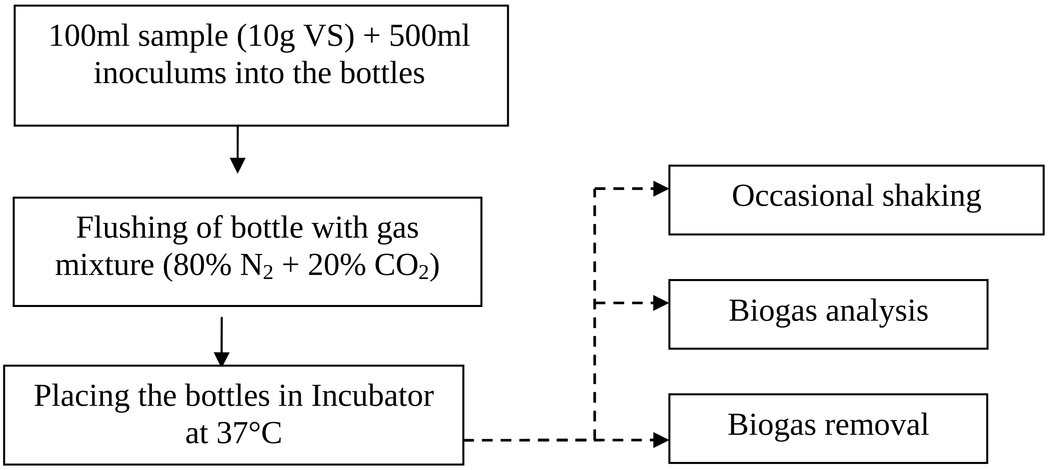


Figure 3.8: Schematic representation of lab-scale BMP assay (Hansen et al., 2004).

3.4.2 Solid waste analysis

Waste characteristic was examined in order to calculate the mass and volume reduction in each operational stage. Figure 3.9 shows solid sample analysis methods. Fresh solid waste as well as digested residue were analyzed, in terms of composition, moisture content (MC), and dry matter (DM), using standard methods. Table 3.3 shows solid waste analysis along with interferences, and precautions during sample handling.

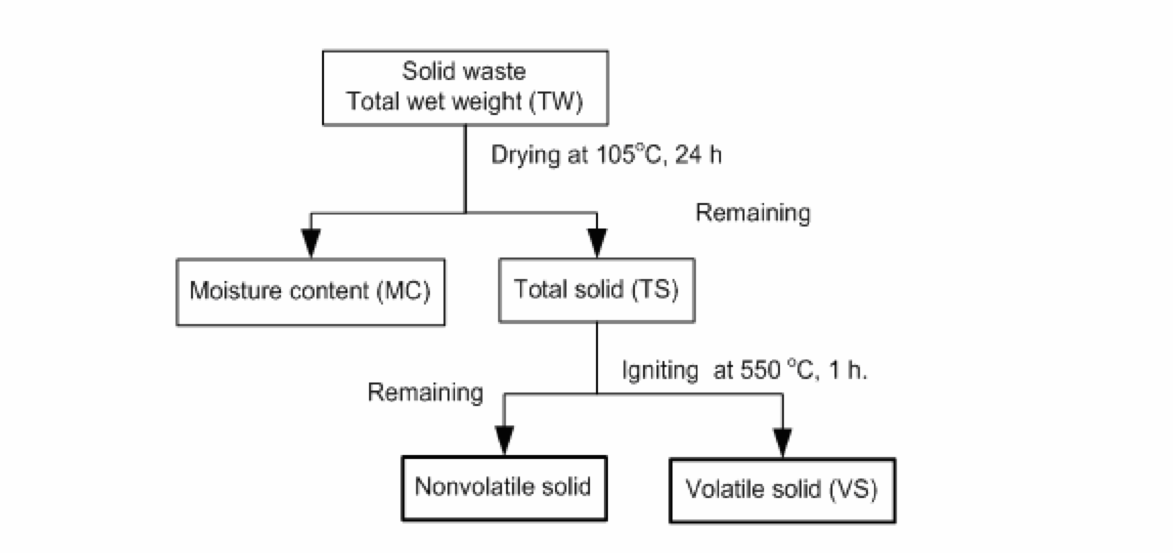


Figure 3.9: Solid waste sample analyzing procedure

Moisture Content Determination

Moisture content is amount of water present in the waste and is expressed in percentage and the remaining portion is the dry matter content as in:

$$\%MC = \frac{1000 - w_o}{1000} x100\% \qquad \text{……………………………Eq. 3.6}$$

where w_o is the weight of the sample after drying. Total solid is estimated by subtracting %MC from 100 as in:

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

Volatile Solids Determination

The volatile solid can be calculated using the following equation:

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

where,

w_o = weight of sample and crucible after 105^{o}C
w_f = weight of sample and crucible after 550^{o}C
w_e = weight of empty crucible

Calculation of %TS and %VS loss

Figure 3.10 illustrates the material balance in digestion process. Feedstock fed into reactor has total weight of TW_o and dry weight M_o. After being digested residual will have total weight TW_1 dry weight M_1 which are less than TW_0 and $M_{o,}$ respectively. The following equations will be used to obtain percentage total solid loss (%TS loss) and percentage volatile solid loss (%VS loss).

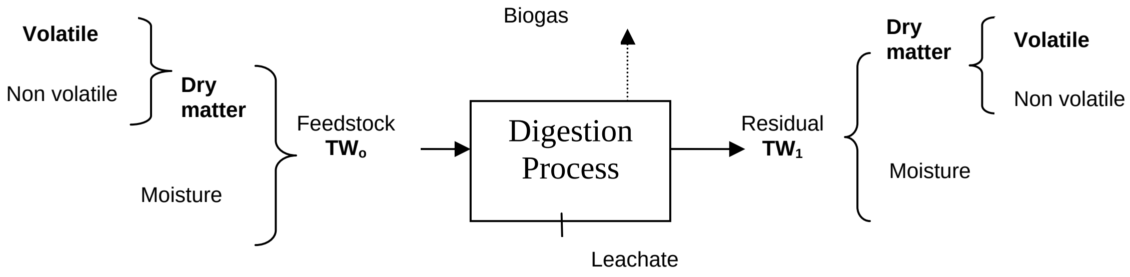


Figure 3.10: Material balance in anaerobic digestion process

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

where, M_o= dry weight of feedstock going in reactor, g

$M_o = TW_o \text{ x } TS_o \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$ Eq. 3.10

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

TS_o: % total solid of feedstock (%TW)

M_1: dry weight residual going out reactor, g

$M_1 = TW_1 \text{ x } TS \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$Eq. 3.11

TW_1: wet weight of residual going out reactor, g

TS_1: % total solid of residual (%TW)

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

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

$N_o = M_o \text{ x } VS_o$ ……………………….Eq. 3.13

VS_o: % volatile solid of feedstock (%TS)

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

$N_1 = M_1 \text{ x } VS_1$ ……………………………………………Eq. 3.14

VS_o: % volatile solid of residual (%TS)

3.4.3 Leachate characteristic analysis

Focus of the laboratory analysis in pre-stage was on the hydrolysis and acidification of the solid. Only leachate analysis was carried out in the first stage; gas production being negligible, was analyzed. pH, ORP will be measured in the field at the time when samples are taken. Parameters to be analyzed are

- Total dissolve organic matter: DOC and/or COD;
- Volatile fatty acids: acetic acid propionic acid butyric acid and valeric acid
- Alkalinity
- Dissolve nitrogenous compounds: NH_4-N, TKN;
- Total Dissolved Solid

Table 3.4 summarizes the analytical methods including the application range, the interferences as well as precautions during sampling and analysis.

3.4.4 Biogas analysis

Gas production was monitored daily on-line with a wet gas meter (Ritter TG 05, Germany). Biogas was sampled by inserting gas syringe into U tubes, volumetric composition of biogas (H_2, CO_2, CH_4, O_2, N_2) sample was analyzed daily by using Gas Chromatograph (SHIMADU-GC14A, Japan) equipped with thermal conductivity detector. Gas composition was analyzed for hydrogen, methane, carbon dioxide and nitrogen. Table 3.5 depicts the method, instrumentation and precaution during sample handling. Gas flow rate and composition is required for calculation of specific gas production (SGP) and gas production rate (GPR). Table 3.6 shows the analytical conditions of GC. Ambient temperature and pressure were measured in order to calibrate to standard condition (°C and 1013.25 *mb)* recommended by International Union of Pure and Applied Chemistry (IUPAC). The volume of the gas at STP was calculated by using the equation given below.

$$V_{STP} = V_m \frac{T_S . P_m}{T_m . P_S} \qquad \text{…………….. ………….. Eq.3.15}$$

Where T_m = Ambient(measured) temperature (K)
P_m= Ambient pressure (measured)
V_m = Volume of gas measured at ambient condition
T_s= Standard temperature (0°C = 273K)

P_s= Standard pressure (1013.25 *mb)*

Since digester gas usually was saturated with water vapor, dry volume of the gas was calculated using the equation below.

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

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

3.4.5 Post digested analysis

Physical properties like Moisture Content (MC), Volatile Solid (VS) and Total Solid (TS) of digestate waste were analyzed after digestion completion in batch process.

3.5 Post-treatments of digestate

Post treatment of digestate waste, from both batch as well as continuous process, was carried out. Digestate waste from continuous operation was air dried after dewatering in sand-drying bed. Some samples from both processes were analyzed for total organic carbon, nitrogen, phosphorus using standard procedures recommended by American society of Agronomy and heavy metals after 2 weeks of curing. Table 3.7 presents sample analysis methods along with precaution during sample analysis and handling. Calorific values were analyzed using bomb calorimeter (CAL2k- ECO).

Table 3.3: Solid waste analysis

Test Parameter	Method/ Instrumentation	Minimum sampling size	Applicable range and accuracy	Interferences
Moisture content (%)	Oven (105°C) for 24hrs Gravimetric analysis	1 kg	Heating and cooling till change in Weight <3%	Improper sampling procedure, sampling bottle, sample handling, weighing
Total solids (%)	Gravimetric analysis	1kg	-do-	-do
Total volatile solids (%)	Muffle furnace (550°C)	2 g	-do-	-do-

Table 3.4: Leachate characteristics analysis

Test Parameter (unit)	Method/ Instrumentation	Preservation & Recommended max. storage	Applicable range and accuracy	Interferences	Precaution during sampling and analysis
pH	pH meter (pH 330 i, Germany)	Immediate analysis	(1-14) ±0.1	Sodium if pH>10 Temperature	Periodic Meter calibration
COD (mg/L)	Standard method 5220C: Closed reflux titration method	Refrigeration (4°C), 7 days	>50mg/L, not applicable if Cl^- >2000 mg/L	Halides ions like Chloride Nitrite (NO_2^-)	Addition of $HgSO_4$ to eliminate Cl^- , Sulfamic acid addition to remove NO_2^-
TOC /DOC (mg/L)	High temperature combustion method (SHIMADZU TOC-V_{CSN} Non-dispersive infrared analyzer detector with standard TC catalyst)	Refrigeration (4°C), 7 days	>20 ppm 5-10%	Inorganic carbon	Acid addition to pH 2 and purging of acidified solution
Alkalinity (mg/L as Ca CO_3)	Standard method 2320 B: Titration method	Refrigeration 24 hr		Soap, oily matter, suspended solids	Use of pH meter along with indicator for turbid samples
VFA (mg/L)	Gas Chromatograph (SHIMADU-GC14 A with TCD detector)	Immediate analysis	Instrumental operation and calibration curve	Presence of synthetic materials like detergents	
TKN (mg/L)	Standard method 4500B :Macro kjeldahl method	Refrigeration, 24 hours	<5mg/L	Nitrate>10mg/L , inorganic salt and solids	Blank is always necessary
NH_4-N	Standard method 4500B: Distillation method				

Table 3.5: Biogas analysis

Test parameter (unit)	Method/Instrumentation	Interferences	Precaution during sampling and analysis
Flow rate (L/day)	On-line Gas meter (Ritter TG-02 , Germany)	Parallax error	
Composition of different gas (%)	Gas Chromatograph with TCD detector	Instrumental operation and calibration curve	Immediate analysis after sampling

Table 3.6: Analytic condition for Gas chromatography

Description	Biogas	Volatile fatty acis (VFA)
Detector	Thermal conductivity dectector (TCD)	Flame ionization dectector (FID)
Carrier Gas	He	N_2
Flow rate	40 mL/min	40 mL/min
Injection /Detector Temp (°C)	50 / 100	210/210
Column Temp (°C)	50	100-130°C, 10°C/min,130°C (5min) to 175 , 10°C /min, 175°C (7.5 min)
Column	Pack (WG-100, SUS col., Inner diam.×1.8 m	Capillary, DBFFAP(30m×innner diam.0.32mm× film thickness 0.25μm
SampleVol (mL)	0.2	0.001

Table 3.7: Digestate Analysis

Test Parameter	Method/Instrumentation	Precaution during sampling and analysis
Nitrogen (%)	Total Kjeldahl method	
Phosphorus (%)	Acid digestion /spectrophotometer	Not to boil to dry
Potassium	Acid digestion & Inductively coupled plasma method: 3120B	Not to let it dry during digestion
Heavy metal (mg/kg)	Nitric acid digestion: 3030E/ PerkinElmer (Optima 2100DV) ICP-OES	Not to let it dry during digestion

Chapter 4

Results and Discussions

This chapter presents findings from pilot scale sequential batch anaerobic digestion (SEBAC) experiments and continuous anaerobic digestion (AD). The experiments on SEBAC as well as continuous anaerobic digestion were performed under thermophilic temperature conditions. In the later part of this chapter, results from laboratory scale Biochemical Methane Potential (BMP) are also described. BMP values were used to evaluate the process efficiency.

4.1 Sequential Batch Anaerobic Digestion (SEBAC)

4.1.1 Feedstock characteristics

Solid waste was collected from Taklong municipality dumpsite. Analysis of feedstock samples was carried out in duplicate and results are presented in Table 4.1 as average values.

Table 4.1: Solid waste characterization

Cycle	Fresh waste Reactor	Moisture content (% MC)	Total solid (% TS)	Total volatile solids (% TVS)	Non-volatile solids (% inert materials)
0	R2	80.6	19.4	80.5	19.5
I	R2	87.2	12.8	75.4	24.6
II	R2	88.2	11.8	75.2	25.8
III	R2	87.7	12.3	81.1	21.9

Comparing this result with previous studies in market waste, organic fraction of municipal solid waste (OFMSW) has higher total solid content compared to only 8-9 % in market waste.

4.1.2 Performance of pre-stage operation in reduced particle size

The primary objective of the first run of SEBAC experiment is to generate mature leachate and get an old stabilized reactor. Shredded feedstock of about 10 mm average size was used for the experiment. The reactor was started with flushing for 3 days in order to prevent the accumulation of VFA that can inhibit the process. Flushing gave positive result in a combined process in which acidogenesis and methanogenesis both takes place in the same reactor. The flushing mechanism can help enhance acid as well as prevent VFA accumulation (Lien, 2004). When the system is shifted to methane phase, it will provide suitable condition for methanogens to grow.

During three days of flushing, TCOD, SCOD, NH_4-N, TKN, TDS, Alkalinity, VFA and DOC were monitored (See Appendix, Table C-2). Figure 4.1 shows cumulative pollutant loads in leachate during three days of pre-stage operation. As much as 234g of TCOD, 196g of SCOD, 161g of TDS per kilogram of total solid could be removed from three days of flushing. Likewise, considerable amount of NH_4-N (18.8g) and TKN (27.3g) were removed from flushing for every kg of total solid load. The concentration of various pollutants as obtained in 3 days of flushing is presented in Figures 4.2 and 4.3. As a general trend, the pollutant load concentrations increased substantially after a day of flushing at day 2 but the concentration decreased at day 3. It is noted here that 180 L of water was used to flush the waste bed which was replaced at day 2 of flushing. Figure 4.2 displays the daily generation load of TCOD, SCOD, VFA, DOC and TDS in leachate. As shown in the Figure 4.2, the concentration of pollutants, TCOD, SCOD, DOC, and TDS in particular, increased from day 1 to day 2. In the similar manner ammonium nitrogen and TKN showed marginal increment from day 1 to day 2 whereas small decrement was noticed when fresh water was used for flushing at day 3 (Figure 4.3). The reduced concentration at day 3 signifies that large amount of pollutants were already leached out from the system. The concentration of VFA was also found to exhibit similar trend. Total VFA reduced from 6.3 g/L to 5.3 mg/L after 3 days of flushing period generating a cumulative load of 151 g/kg TS. Alkalinity, however, decreased with time gradually from 2300 mg/L at day 1 to 1800 mg/L at day 3. This is because during the pre-stage hydrolysis process causes the pH to increase thereby decreasing the alkalinity.

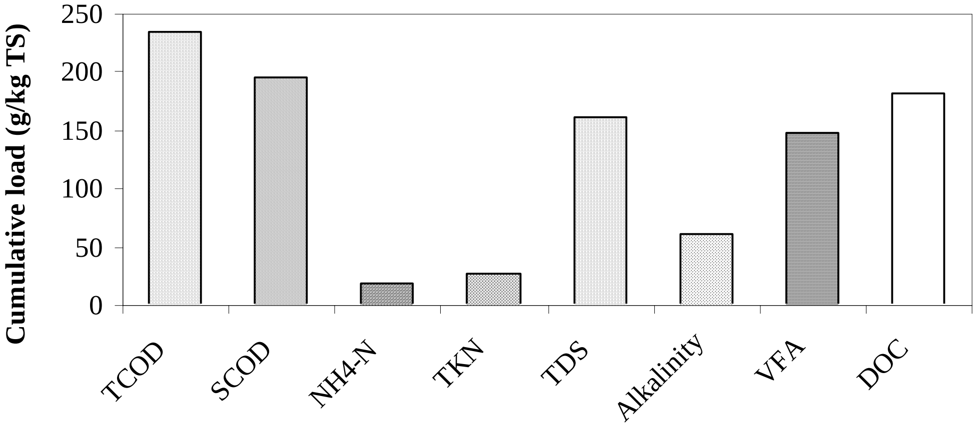


Figure 4.1: Cumulative pollutant load removed after pre-stage

Juanga (2005) reported that operating temperature and particle size greatly influence the efficiency of pre-stage operation. Research conducted under thermophilic condition on OFMSW resulted into higher pollutant load removal as opposed to the ambient and mesophilic temperature. Cumulative pollutant loads removed in this study were found 20 % higher than the ones reported by Juanga (2005). This could be because the particle size used in this study was 10 mm which was much smaller (3 times) even though the operating temperature was mesophilic. Dayanthi (2003) also reported higher leaching of pollutants in 10 mm size compared to 30 mm.

According to Miron et al. (2000), highest increase in hydrolysis of total COD could be obtained at retention time of 3 days. A pH value of 5.6 was obtained for the system after 3 days of pre-stage operation. As pH range for methanogens is 6.5- 7.3, the system required pH adjustment. The pH of the system was adjusted to 7.0 using commercial grade sodium hydroxides (NaOH). Later, 20 kg of inoculum (10% waste) was added in day 5. Details on pH adjustment and inoculum addition are presented in chapter 3, section 3.2.3. The system was left for methanogenesis to occur.

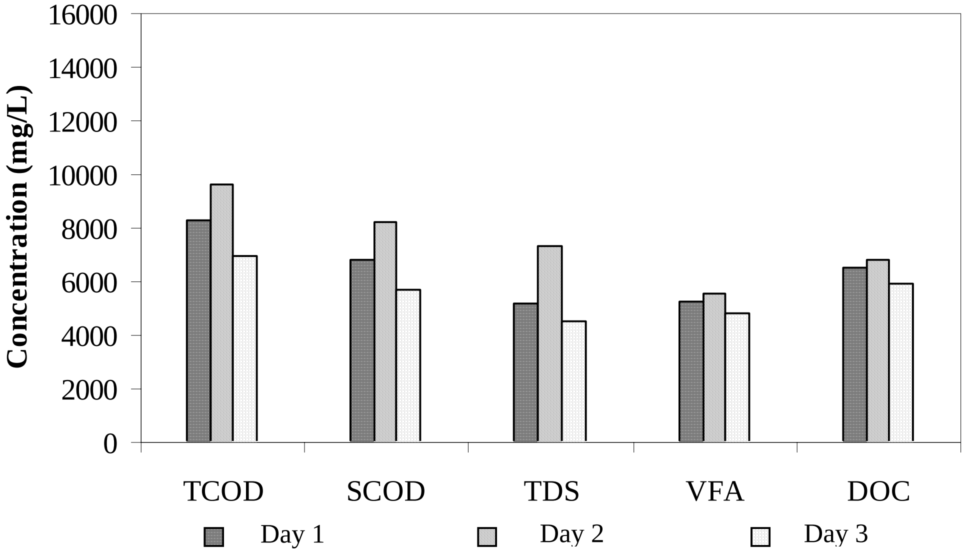


Figure 4.2: Pollutant (TCOD, SCOD, TDS, VFA and DOC) concentration during flushing

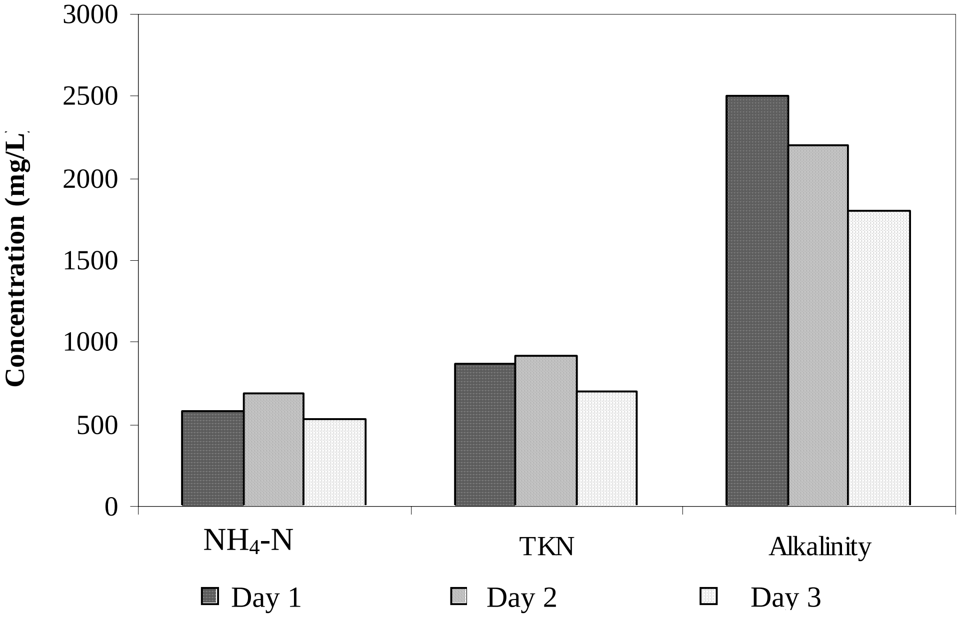


Figure 4.3: Pollutant (NH_4-N, TKN and Alkalinity) concentration during flushing

4.1.3 Mature phase biogas production: Run I

Biogas production and composition was monitored daily. The volume of the gas produced was converted into standard temperature and pressure conditions (0°C and 1 atm.) for uniformity and comparison (Table C-1). It was observed that after 40 days, methane concentration reached 50% of the biogas produced and this stage was considered the beginning of mature phase. Figure 4.4 shows daily gas production in different operating temperature. Mesophiic condition was switched to thermophilic by increasing a temperature of 2°C per day until it reached thermophilic (55 °C). As shown in the Figure

(4.4), daily gas production increased steadily during transient and thermophilic condition. The increase in gas production was significant as the process became fully thermophilic. Increase in percentage of methane (CH_4) in gas composition was also observed.

Figure 4.5 illustrates cumulative biogas production. Under mesophilic condition, the cumulative biogas production at 40 days was 1250 L; this value almost doubled in 9 days of transient period, and increased exponentially to 7000 L at the end of 75 days of operation that corresponds to the 257 L of biogas/ kg VS at STP (0°C and 1atm. pressure). When thermophilic condition prevailed, in 33 days of operation 5200 L of biogas was produced compared to 1900 L in 48 days of mesophilic and transient condition. As observed, commencement of the thermophilic condition gives higher biogas yield. Juanga (2004) reported maximum daily gas production of 300 L/day under thermophilic condition with 30 mm feedstock size. However, with the feedstock size reduced to 10 mm in this research, daily gas production of as high as 400 L/day could be observed. This finding is in line with Ghosh et al. (2000) who reported that decreasing particle size had no beneficial effect on mesophilic condition but methane yield increased on thermophilic condition. Bouallagui et al. (2004) found that biogas production rate in thermophilic temperature was higher by 41% in average compared to the biogas production rate from mesophilic digesters. This result can be related to the findings of Valdez-Vazqueza et al. (2005) who observed significantly higher hydrogen yield in thermophilic condition compared to mesophilic. Converti et al. (1999) suggested that the thermophilic micro-flora have the capacity to use several sources of carbon than the mesophilic micro-flora.

Cecchi et al. (2003) reported an unbalanced situation for a few days after shifting the operating condition from mesophilic to thermophilic in short period (within 48 hours). Because the increase in temperature in this experiment was gradual, stress situation was not observed, and gas production was not affected. Slowly increased digester temperature appears to favor development of truly thermophilic species over thermotolerant mesophiles. One added bonus of such approach is the time and cost associated with preparing theomorphic seed culture is eliminated. This experiment confirms that long time acclimatization of inoculum can be avoided.

4.1.4 Mature leachate characteristics: Run I

Mature leachate analysis results from the first run are presented in this subsection. Parameters such as pH, Alkalinity, VFA, DOC, and NH_4-N were monitored (Table C-3). Variations in pH of the mature leachate are illustrated in Figure 4.6. During early phase of maturity, pH in leachate increased rapidly. However, pH remained steady state at 7.8 and never reached the threshold value of 8 and beyond at which the leachate becomes toxic. This is an indication of the system not being under stress. Change in VFA, DOC, alkalinity and ammonia concentration of the mature leachate is presented in Figure 4.7. Both VFA and DOC concentration remained constant initially but showed slightly decreasing trends after 45 days. Ammonia and alkalinity on the other hand increased considerably. Ammonia concentration which was 800 mg/L at 40 days increased to 950 mg/L in the next 15 days. Similarly, alkalinity increased considerable from 4500 mg/L to 7000 mg/L during the same period. This shows that system has enough buffering capacity.

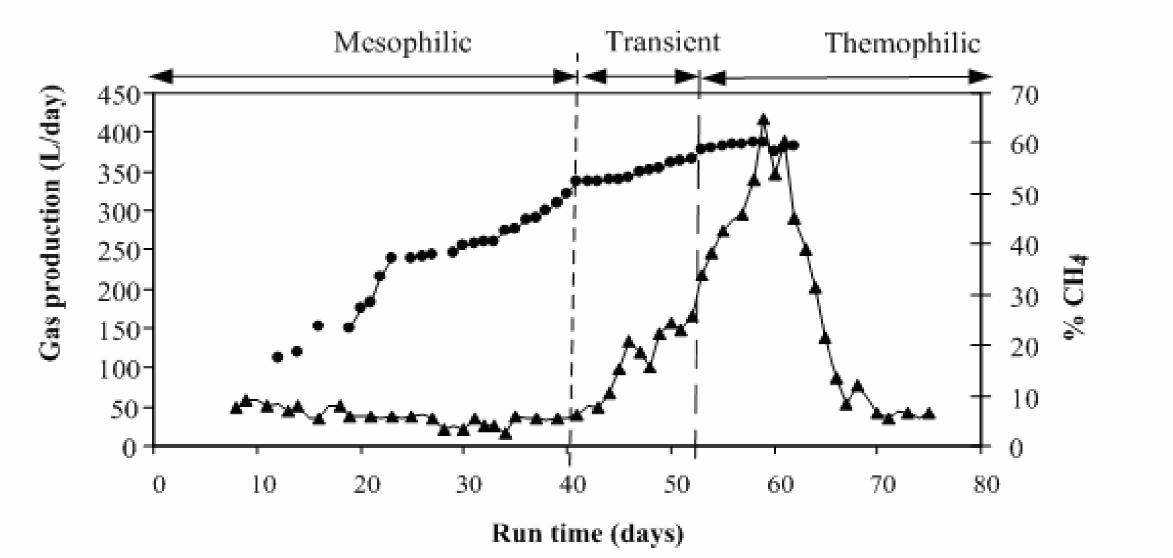


Figure 4.4: Daily biogas production during different operating temperature

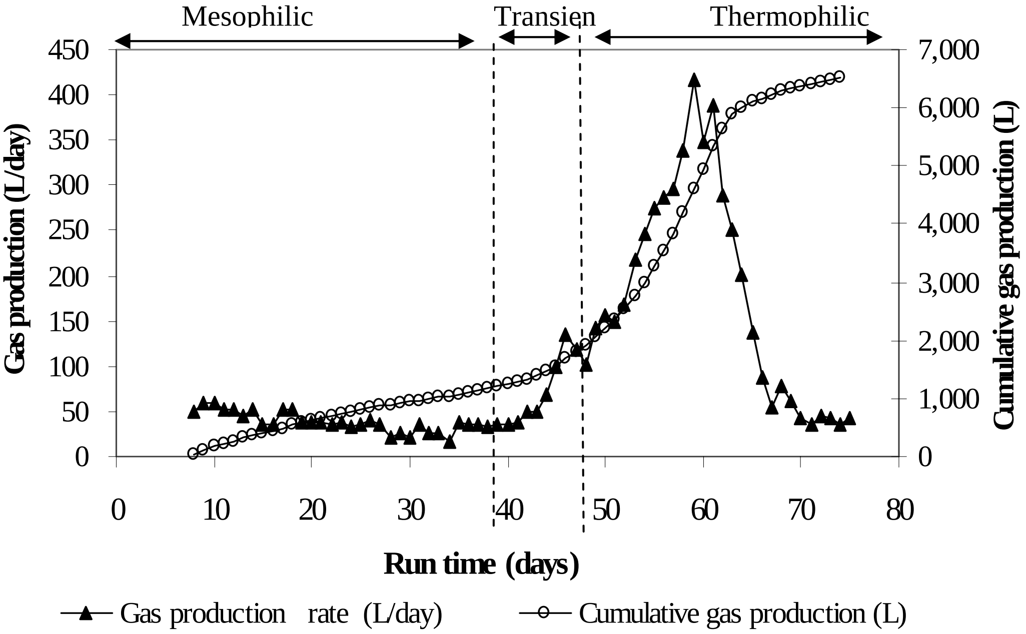


Figure 4.5: Daily and cumulative gas production

The effect of particle size reduction was studied by comparing the result of previous study (Juanga, 2005) with 30 mm particle size as opposed to 10 mm size in this run. However, due to some technical problem associated with reduced particle, consecutive experiments (SEBAC) were carried out in 30 mm particle size of the substrate.

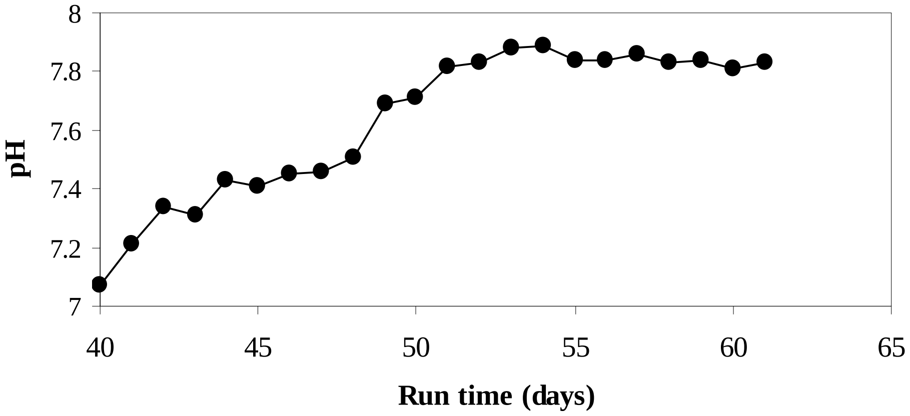


Figure 4.6: Variation of pH with time

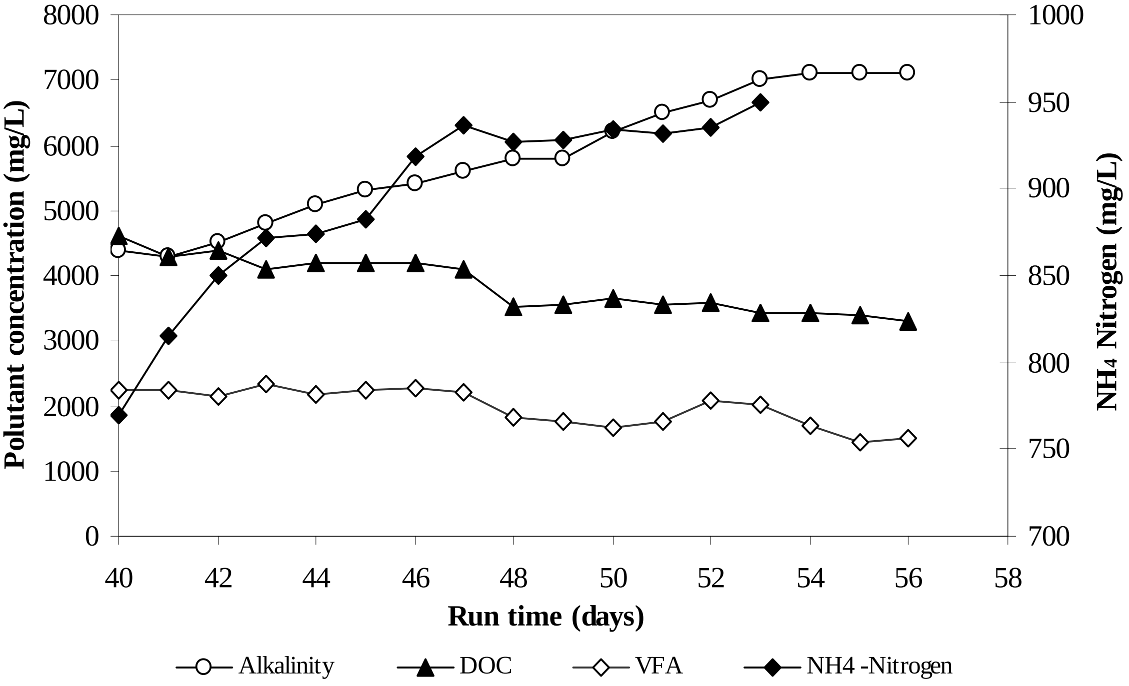


Figure 4.7: Leachate Characteristics

4.1.5 Sequential Batch Anaerobic Digestion (SEBAC): Cycle I

Referring to Figure 4.5, biogas production was observed to have been exhausted after 75 days of digester operation. This old reactor is now considered stabilized and it is ready to be coupled with a new reactor to start-up SEBAC experiment. The new reactor was started by using the effluent leachate from stabilized reactor. Leachate from the fresh waste reactor, which contained high concentration of volatile fatty acids, was fed into the stabilized reactor. It is hypothesized that during sequencing, leachate that flushed out of the old reactor carries with it micro organisms, nutrients and buffering agents to the new reactor, thereby rapidly inoculating it and promoting balanced growth of microbial consortia. Also, the products of solublisation and fermentation are flushed out of the new reactor into the stabilized reactor where it is converted into methane and carbon dioxide.

After pH of leachate from the fresh waste reactor reached 7, reactors were uncoupled and direct circulation of leachate was allowed. It took 7 days for the pH to reach 7, and, accordingly reactors remained coupled for 7 days. Juanga (2005) applied SEBAC operation on market waste for which 9 days of coupling was required to arrive at the desired level of pH. Norphratana et al. (1997) mentioned that it took 12 days to reach the pH of leachate 6.5 and 10 days to reach 30 % methane in biogas. Chugh et al. (1999) reported that 9 days of coupling is sufficient to inoculate and bring new reactor to its active methane phase. Sequencing period depends on the volume of leachate that is recirculated and could last anywhere between 8 and 25 days (Nopharatana et al., 2003). In this cycle recirculation rate was 3 L/min for 30 minuets (0.34 m^3 leachate / m^3 of waste per day).

1. Leachate characteristics: Coupled and uncoupled reactors

Details on parameters pertaining to leachate characteristics are included in Appendix (Tables C-4 and C-5). The variations in pH and alkalinity during start-up are shown in Figure 4.8. The pH value of 7 and the methane content of 50% were taken as signs of active methane phase. The reactors were uncoupled at this stage as described earlier. In the new reactor (reactor 2), pH started to increase and remained within a close range of 7.5-8.0 throughout the digestion process. Leachate from old reactor containing buffer, nutrients etc caused the pH to rise. However, within a couple of days the readily soluble organic matter gets fermented to volatile organic acids, and, when the acid concentration exceeds the buffering capacity of the leachate, the pH drops. Though drop in pH value was observed in day 4, it was within the neutral value. It is argued that the sequencing process seeds the new reactor with methanogenic inoculum from the old reactor. Once the methanogenic bacteria begin to consume the volatile organic acids to produce methane, the pH of the leachate climbs back up. Sustained methane production can be obtained at the pH of around 7.5.

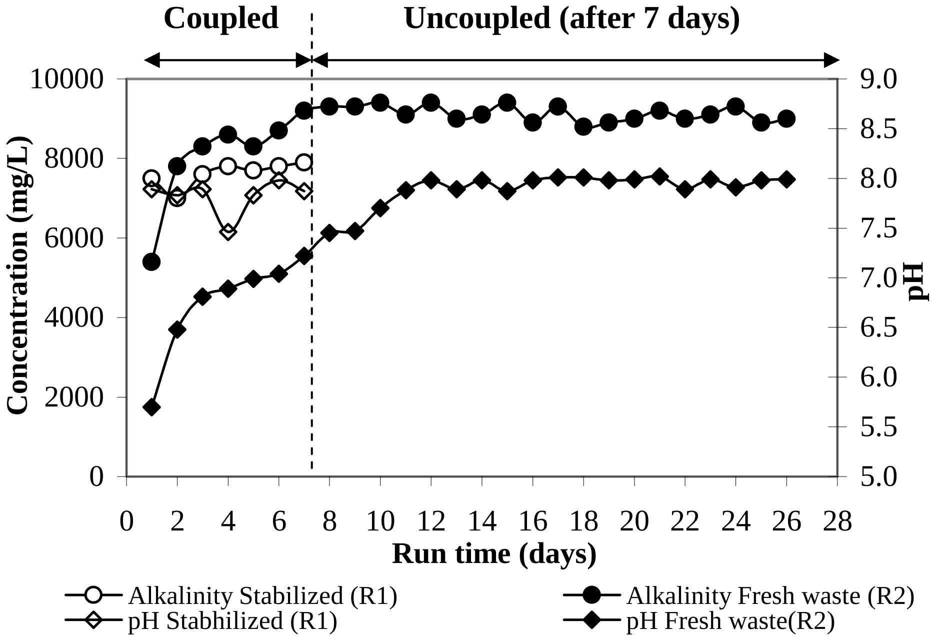


Figure 4.8: Variation in pH and alkalinity during and after coupling

The old reactor (reactor1) also exhibited a stable condition; pH >7 was observed during cross-recirculation. Accumulation of VFA and DOC was not significant to cause the instability of the process. Figure 4.8 shows that alkalinity of the new reactor started to increase from 5000 mg/L and remained around 8500-9000 mg/L indicating that system has enough buffering capacity.

The presence of NH_4-N can always be of concern in anaerobic digestion as free ammonia can be inhibitory. In this experiment concentration of NH_4-N increased from 780 mg/L upto 1300 mg/L and then remained leveled off to around 1100 mg/L at the end of the process as illustrated in Figure 4.9. This was below the inhibitory concentration 1500 mg/L. The oxidation reduction potential (ORP) is a performance parameter for anaerobic digestion which measures the electron activity in aqueous environments. Methanogenic bacteria are the most sensitive to elevated ORP levels and an increase in this parameter suggests that they are inhibited and the consortium is imbalanced. Figure 4.10 indicates the ORP value along with time of operation. For the reactor 1, being the old and the stabilized one, ORP value is below -300 mV. The new reactor showed the ORP value of -95 mV in the first day of coupling. The ORP value reached below -300 mV on day 6 and remained in the range of -350 mV to -400 mV.

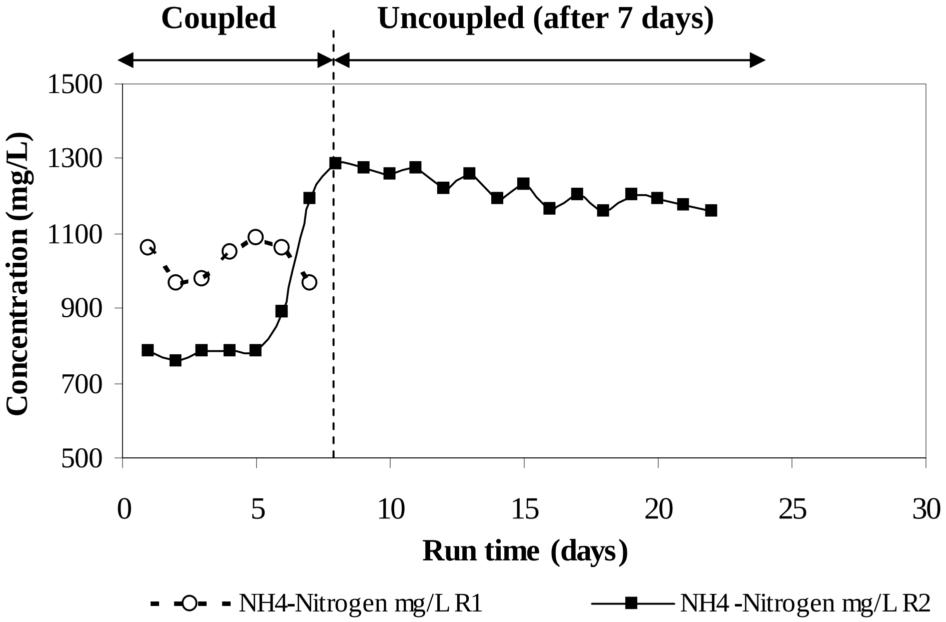


Figure 4.9: Variation NH_4-N concentration during operation

The concentration of VFA is one of the most important parameters of monitoring because the elevated levels are the indication of the process instability. In this experiment accumulation of VFA and DOC was not significant and concentration reduced as digestion time proceeded. Decreasing trends of DOC and VFA along with increase in production of methane indicates a stable system. DOC and VFA concentration were higher in the start up of the digestion in the new reactor. VFA concentration in the reactor 2 (new) was found 3700 mg/L on day 1 but remarkably reduced to the level as low as 400 mg/L at the end of the operation. Unstable situation in the reactor 1 (old) was not observed as significant accumulation of VFA and DOC was not found as presented in Figure 4.11.

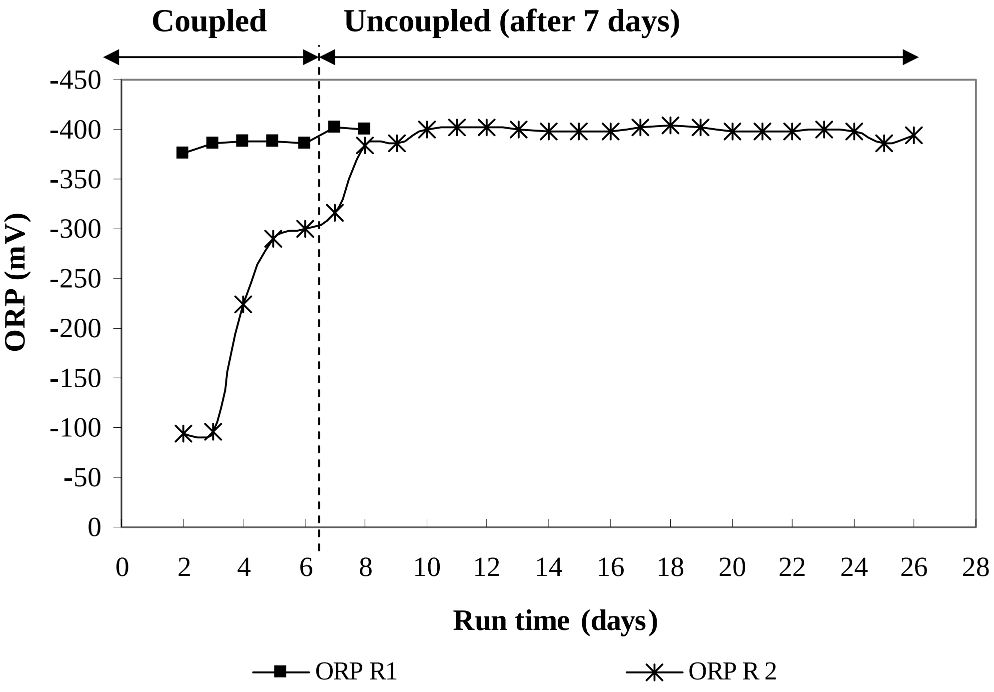


Figure 4.10: Changes in ORP during process

2. Biogas production: Coupled and uncoupled reactors

Gas production is the parameter that shows digester instability faster than pH monitoring. Biogas production was monitored daily from wet gas meter during coupling as well as after uncoupling in fresh and stabilized reactors (Tables C-10 and C-11). Cumulative gas generation was calculated as combined production from both reactors (R1+R2). The production is entirely attributed to the fresh waste reactor as the stabilized waste reactor exhausted its methane producing potential before coupling.

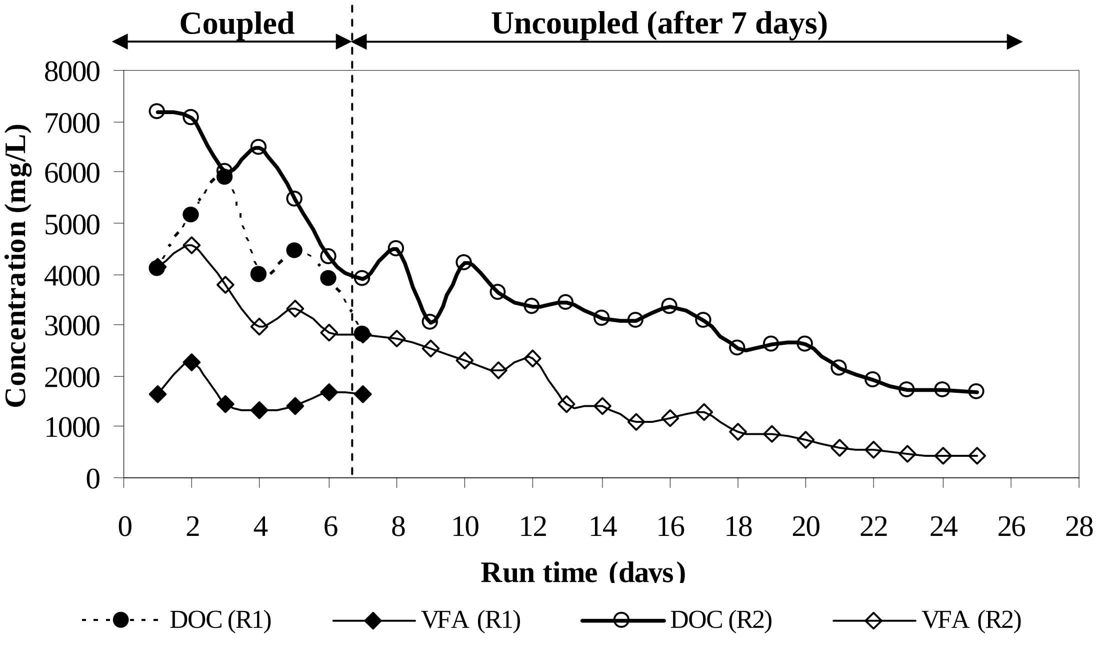


Figure 4.11: Variation in DOC and VFA concentration

Daily gas production, as high as 400 L, was observed in old reactor during coupling. In the new reactor, daily gas production was small in the beginning, started to increase after day 4. Biogas concentration in the methane also started to increase as presented in Figure 4.12. Biogas production reduced significantly after day 26 in the new reactor and day 15 in the old reactor as presented in Figure. 4.13.

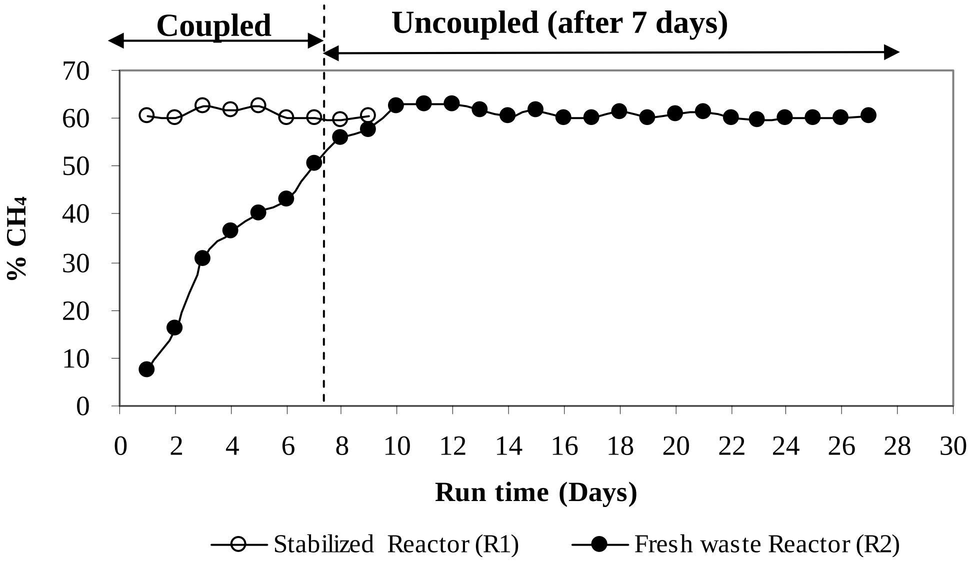


Figure 4.12: Concentration of methane in Fresh waste and stabilized reactors

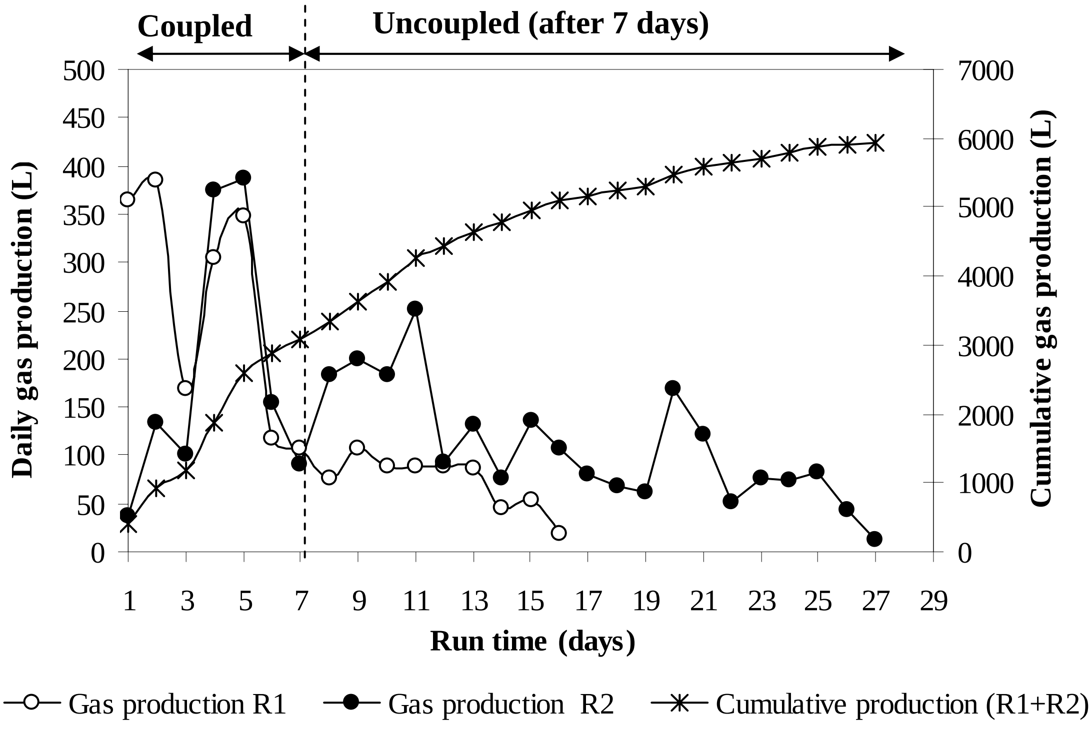


Figure 4.13: Daily and cumulative gas production in old and new reactor

4.1.6 Sequential Batch Anaerobic Digestion (SEBAC): Cycle II

The completion of SEBAC cycle I was marked by nominal biogas yield as shown in Figure 4.13. The stabilized reactor (R1) was connected to the freshly fed reactor (R2) for SEBAC cycle II. The leachate from the stabilized reactor, which contained high concentration of volatile fatty acids, was fed into the new reactor (R2) as in cycle I. The volume of leachate recirculation greatly influences the sequencing period (Nopharatana et al., 2003). In this cycle recirculation rate was increased from 3 to 4 L/min for 30 minuets. (0.46 m^3 leachate / m^3 of waste per day). After pH of the newly loaded reactor reached 7 and methane concentration reached 50 % in biogas, reactors were uncoupled and direct circulation of leachate was allowed. It took 5 days for the pH to reach the value of 7, whereas methane composition reached 50 % only at day 7. Therefore, the reactors remained coupled for 7 days to avoid unbalanced situation in early uncoupling reported by Chug et. al, (2001).

1. Leachate characteristics: Coupled and uncoupled reactors

Leachate characteristic are presented in Appendix (Tables C-6 and C-7). The pH of the effluent leachate from fresh reactor R2 (Figure 4.14) rose form its initial value of 5.46, prior to the commencement of cross-circulation to 6.69 in day 3. It rose steadily to a value 7.05 on day 5. During this period the pH was essentially controlled by the volatile organic acid concentration. On the other hand pH of leachate old reactor before coupling was 8.0. After coupling, pH started to decreased and reached 7.3 in day 2. This pH being within the range (above 7) for methanogens growth, did not affect the process. This drop is due to VFA coming freshly loaded reactor (R2). This drop is pH was short-lived and remain relatively stable again as this system already had enough buffering capacity. Besides, VFA produced was also consumed by old reactor. The exchange of leachate between the fresh-waste and stabilized waste removed VFA from fresh waste through flushing. The alkalinity of the freshly fed reactor (R2) showed similar trend and remained steady state at 9000 mg/L through out the process indicating that system has enough buffering capacity.

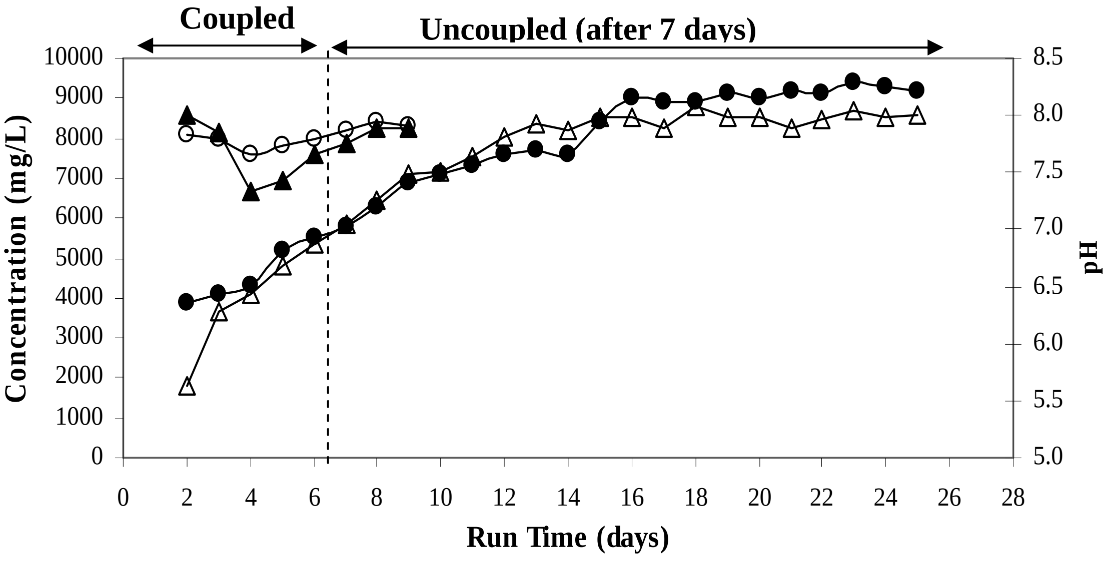


Figure 4.14: Trends of pH and alkalinity in fresh waste (R2) and stabilized reactor (R1)

As a general trend, DOC and VFA increased and showed maximum value in day 3, and then it started to drop. Once the pH of the fresh waste reactor reached neutral value, both DOC as well as VFA showed rapid drop initially but steady drop as the operation proceeded (Figure 4.15). Accumulation of VFA and DOC was not significant to cause the instability of the process. Likewise, NH_4-N concentration increased sharply from 300 mg/L but leveled off to around 1200 mg/L after day 7. This was below the inhibitory concentration of 1500 mg/L in anaerobic digestion (See Appendix, Table C-8).

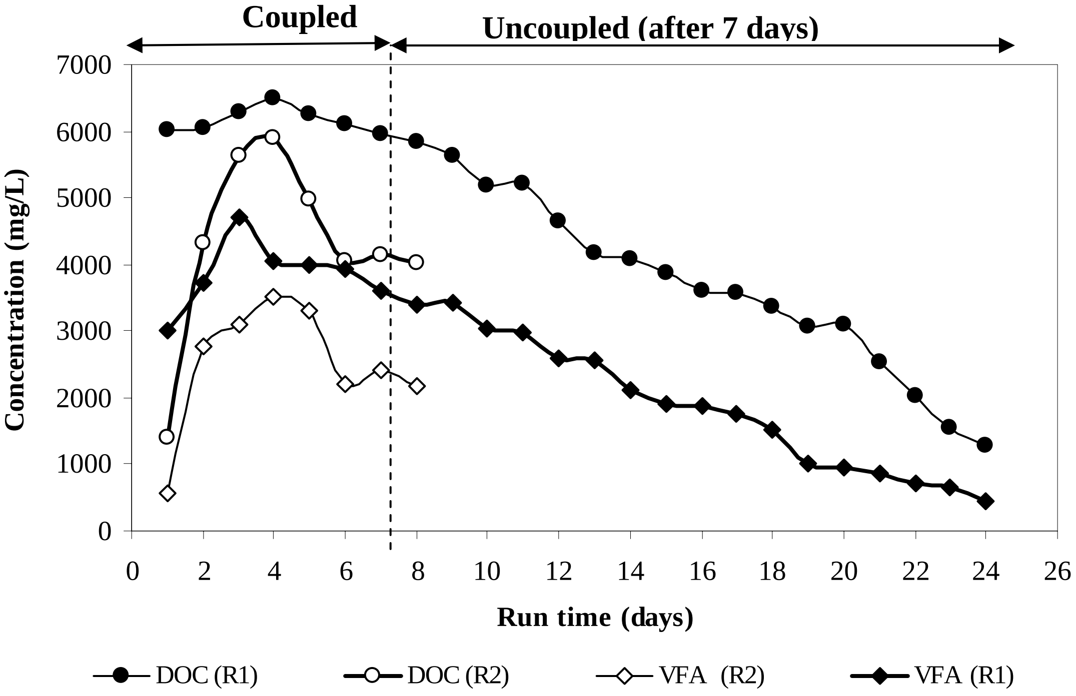


Figure 4.15: Changes in concentration of DOC and VFA in fresh and stabilized reactors

Biogas production

Records of daily biogas generation are given in Tables C-12 and C-13 for stabilized and fresh waste reactors, respectively. Biogas composition reached 50% methane concentration at day 7 and increased to as high as 68 % at day 18. The methane concentration relatively stabilized with values fluctuating in the close range of 65 to 68 % (Figure 4.16). Figure 4.18 shows daily and accumulative biogas production from both reactors (R1 + R2). The accumulative gas production is meaningful because the system is considered single SEBAC system. Biogas production gradually exhausted after 23 days marking the completion of digestion process as seen in the figure. Cumulative gas production of 6670 L was obtained at the end at day 23.

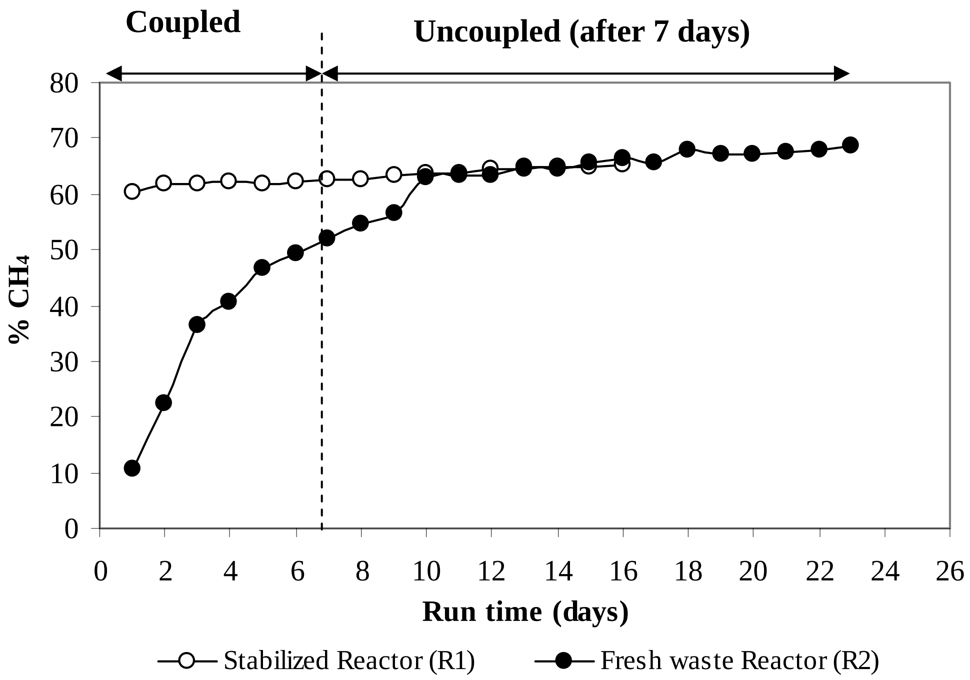


Figure 4.16: Concentration of methane in biogas

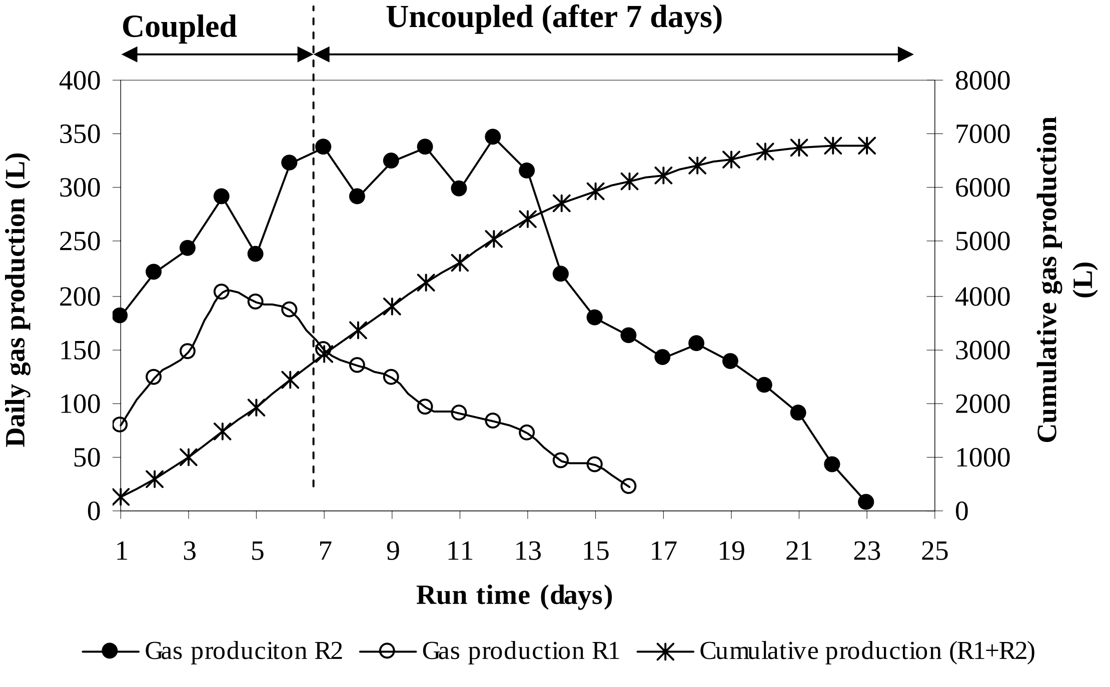


Figure 4.17: Daily and cumulative gas production in fresh and stabilized reactor

4.1.6 Sequential Batch Anaerobic Digestion (SEBAC): Cycle III

Cycle III of SEBAC began once the stabilized reactor from previous experiment cycle II which had already exhausted its methane producing potential. A new reactor was loaded with fresh feed to provide inoculum, buffering and moisture and coupled with the stabilized old reactor. The leachate from the new reactor, which contained high concentration of volatile fatty acids, was fed into the old reactor as in Cycle I and II. The reactors were uncoupled and direct circulation of leachate was allowed once the desired levels of pH and methane composition were achieved. It took 5 days for the pH to reach the value of 7 methane composition also reached 50% on the same day. Therefore, the reactors remained coupled for 5 days. The volume of leachate recirculation greatly influences the sequencing period (Nopharatana et al., 2003). In this cycle recirculation rate was increased from 4 to 5 L/min for 30 minuets (0.58 m^3 leachate / m^3 of waste per day).

1. Leachate characteristics: Coupled and uncoupled reactors

The pH of the effluent leachate from freshly fed reactor R2 (Figure 4.18) rose form its initial value of 5.87, prior to the commencement of cross-circulation to 6.86 in day 2. During this period the pH was essentially controlled by the volatile organic acid concentration. The pH then started to increase as it got buffer form old reactor. The pH value rose steadily to 7.43 on day 5. On the other hand, the pH of leachate in old reactor before coupling was 8.0 which started to decrease and reached 7.4 in day 2 after coupling. The drop is due to VFA coming freshly loaded reactor (R2). This value of pH, being within the range of methogenic growth, did not affect the process. The drop in pH was short-lived and fluctuating to remain relatively stable again as the system already had enough buffering capacity. Besides, VFA produced was also consumed by old reactor. Alkalinity also exhibited the similar trend as shown in Figure 4.18. Ammonium nitrogen concentration increased initially but continued to level off around 1300 mg/L.

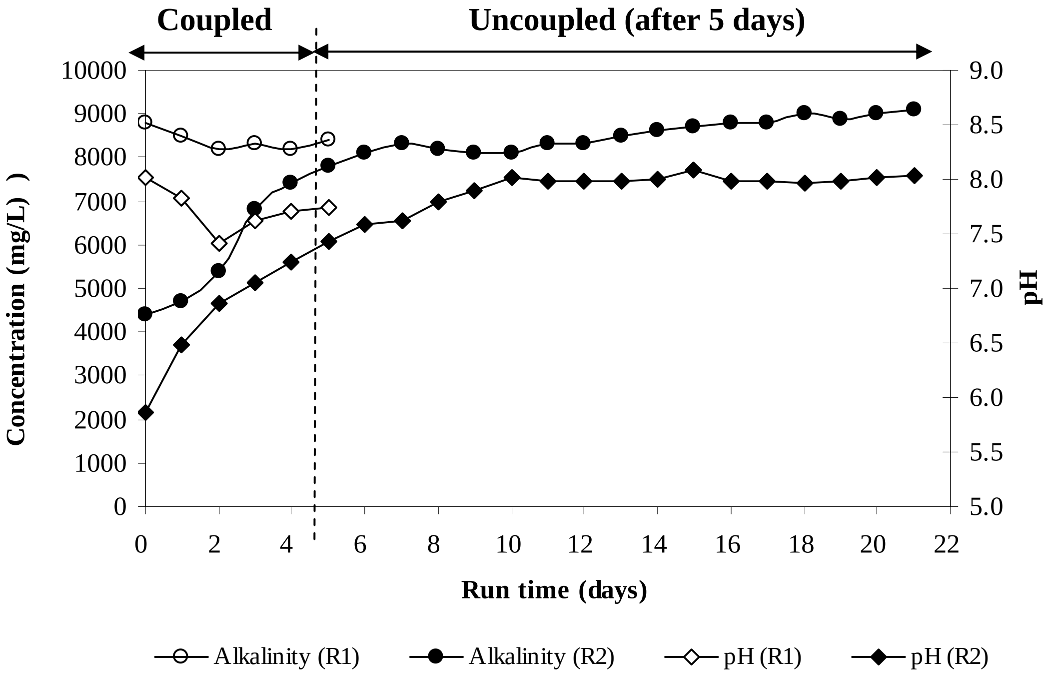


Figure 4.18: Trends of pH and alkalinity in fresh and stabilized reactors

The initial leachate DOC in fresh waste reactor (R2) was very high and decreased progressively until day 10 and subsequently decreased sharply to the value of 1200 mg/L when biogas production was exhausted (Figure 4.19). The concentration of DOC and VFA followed a remarkably close pattern and were almost parallel during the same period. It also indicates that most of DOC is contributed to the volatile organic acids. As VFA is consumed by the microorganisms its concentration started to decreased. Analysis of DOC and VFA in stabilized reactors indicated that concentration of the both the parameters increased initially and peaked at day 3. The increases were short-lived as both the parameters considerably decreased after day 3. The trend of VFA concentration with time clearly showed that passing from the acid phase to the methanogenic phase led to notable decrease in concentrations. This indicated that system was stable and robust.

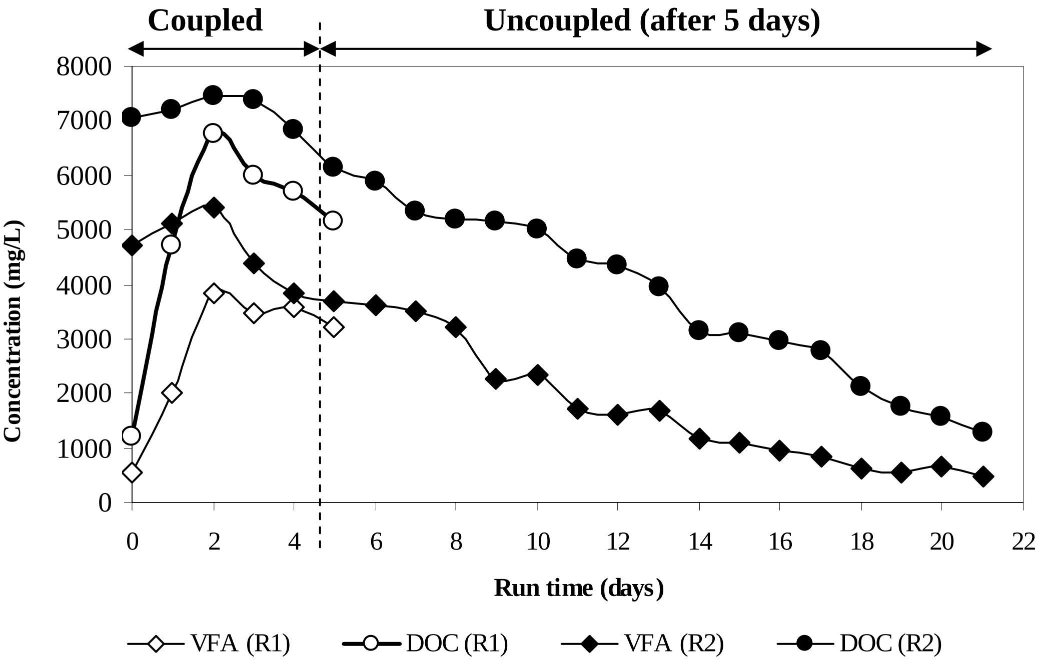


Figure 4.19: Changes in concentration of DOC and VFA in fresh and stabilized reactors

Biogas production

Methane concentration in fresh waste reactor reached 50% in day 5 indicating that system was fully started up (Figure 4.20). In cycle III, most of the methane was produced in the stabilized waste reactor originating from the VFAs passed from the fresh bed as indicted in Figure 4.21 biogas production was exhausted only on day 19, slowly-metabolized compounds might have resulted into a baseline low level of methane production.

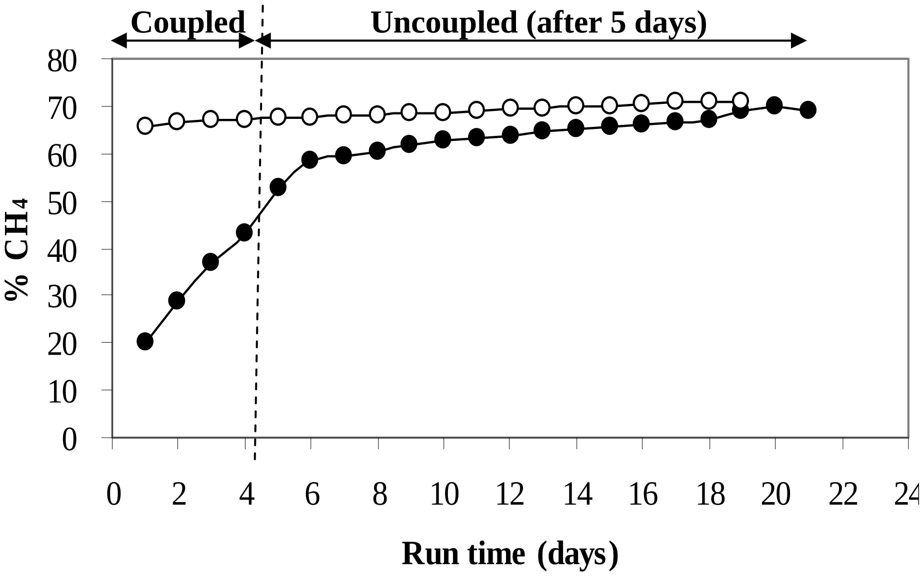


Figure 4.20: Concentration of methane in fresh and stabilized waste reactors

Daily biogas production reached to a very low (13 L) in day 21 indicating that conversion was more or less complete This value started to increased as indicated in Figure 4.21 and reached maximum value of 70% on day 18. Chynoweth et al. (2003) also reported the leveling off of methane yield at about day 21. Daily biogas production in reactors and accumulative biogas production from both reactors (R1+R2) are illustrated in Figure 4.21. The daily biogas production is increased in old reactor after uncoupling and decreased again. Cumulative gas production of 7763 L at STP was obtained as the digestion completed. Interestingly, the digestion completed earlier than the earlier cycles as biogas exhausted in day 21.

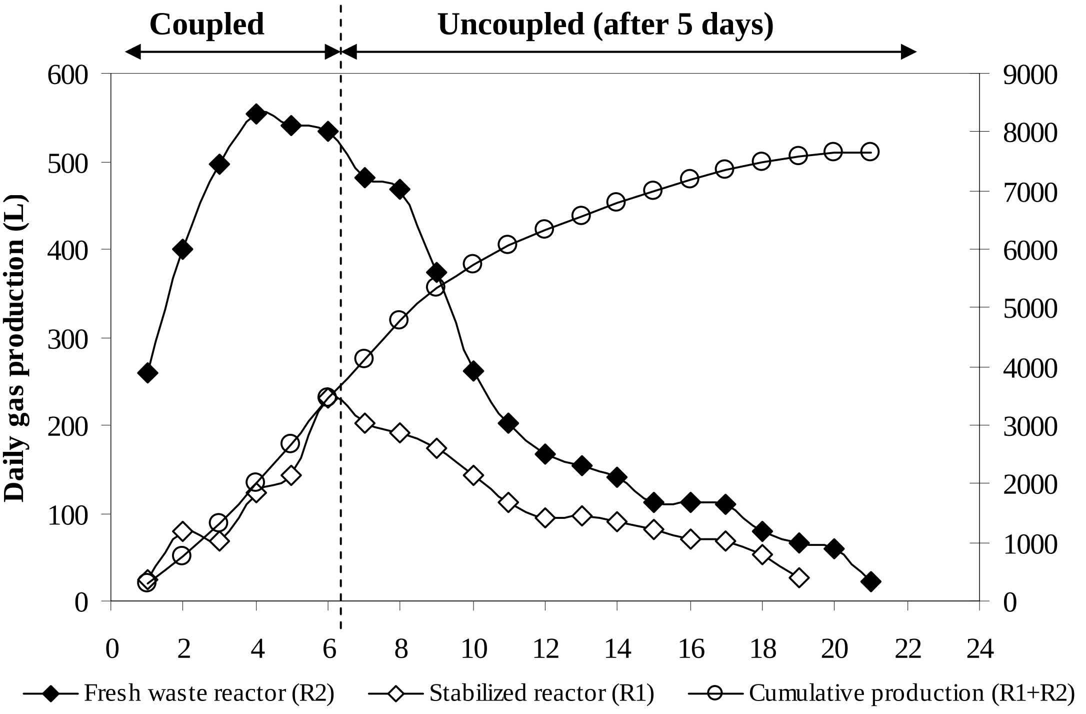


Figure 4.21: Daily and cumulative gas production in fresh and stabilized reactor

4.1.7 Overall SEBAC process assessment

Leachate characteristics: Start-up period decreased down in cycle II and cycle III from 7 days to 5 days, as indicated by reduction in the number of days to uncouple fresh-and stabilized waste reactors (reach the neutral pH). Even though cycle II showed no difference in coupling period due to methane content in biogas reached 50% only in day 7, pH of the fresh waste reactor showed a neutral value 7 on day 5. Therefore, they remained coupled for 7 days. But in cycle III, pH of leachate and concentration of methane in biogas reached 50% on day 5 at which time reactors were uncoupled.

The rate at which balanced conditions are reached in a fresh waste reactor depends upon two factors. One is the rate at which the fresh waste reactor is inoculated and other is the rate at which volatile acids are produced in fresh waste reactor are flushed out. The increase in moisture flow resulted into more rapid degradation of VFA. This may be due to the fact that at higher flushing volumes VFAs are removed and distributed more efficiently, producing better contact with microorganisms. This is supported by the trends of VFA

(Figure 4.22) which drop more rapidly in Cycle II and III compared to cycle I, though drop was less rapid in cycle II compared to cycle III. Also, due to higher circulation rate VFA are removed rapidly from the fresh bed resulting in a favorable environment for the methane formers. The higher flow resulted in the dilution of organic contents thus providing a favorable environment for the growth of microorganism in the fresh waste reactor.

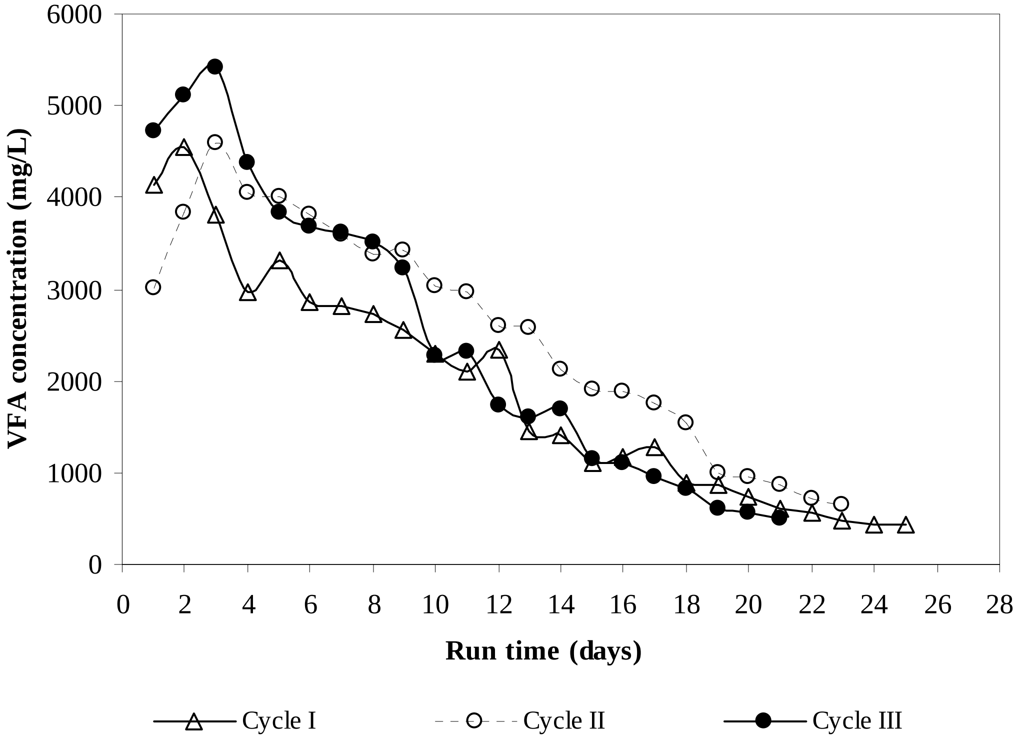


Figure 4.22: Trends of VFA in fresh reactors

Biogas yield: The volume of the gas gas produced (daily and cumulative) produced was normalized and expressed in STP (0°C, 1 atm. or 1013.25 *mb*). Furthermore, biogas production might vary depending upon variation in waste composition; data were further normalized on the basis of the volatile solids added to each of the fresh waste reactors. Cumulative biogas production in cycle III was 7763 L at STP. This value corresponds to 417 L /kg of VS added with 80% volatile solid reduction. Methane content was above 50 % except for first 5 days and reached the maximum value of 70% on day 19. Cumulative gas production in cycle I and II were 5928 L and 6670 L, with specific gas production of 325 L/ kg VS and 395 L/kg VS respectively.

Methane yield of each cycle was calculated as the combined methane production from fresh and stabilized waste reactors. This yield is entirely attributed to the fresh waste bed, as the stabilized waste bed was exhausted of its methane-producing potential before the start of the experiment. Figure 4.24 illustrates that daily gas production rate was higher in cycle III than cycle I and II. The methane content also increased faster and maximum value achieved earlier indicating that increased circulation of leachate though the waste stimulates methogenic activities (Figure 4.23). However, in cycle I daily gas production was fluctuating and higher during premature phase indicating that fermentation of organic was the main reaction with higher percentage of carbon dioxide in the gas.

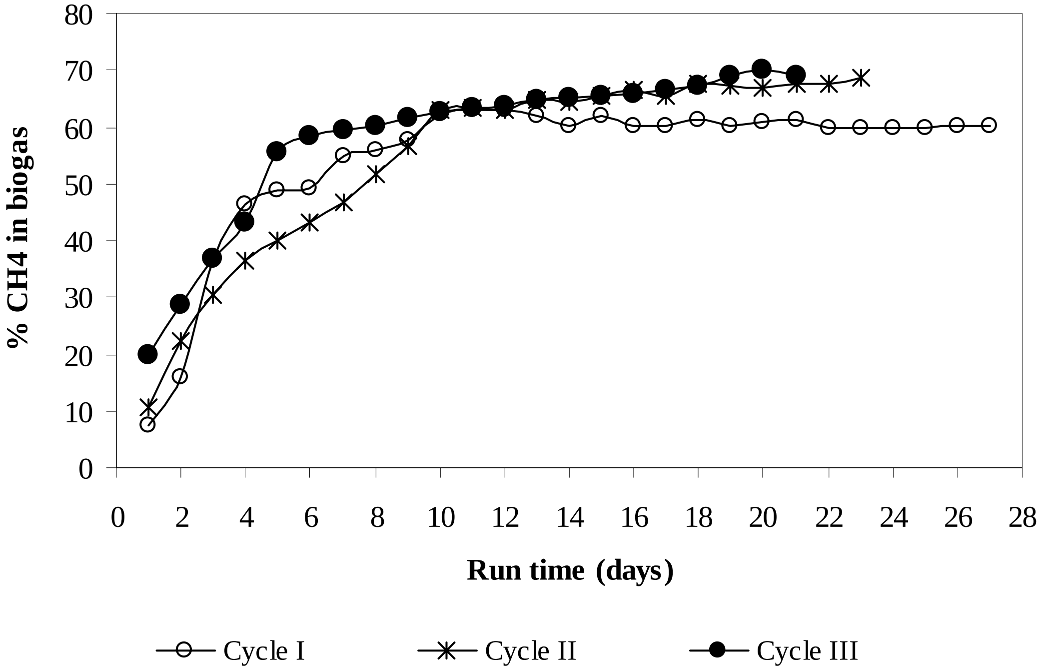


Figure 4.23: Trends of CH_4 composition change in fresh reactors

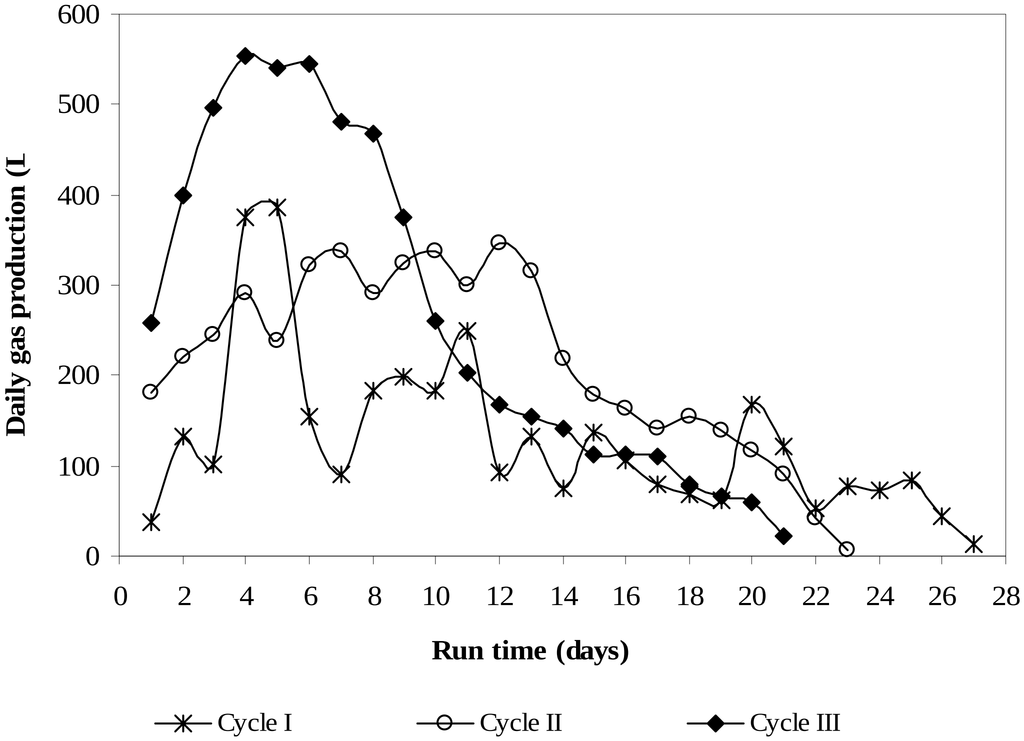


Figure 4.24: Daily gas production trends for fresh reactors

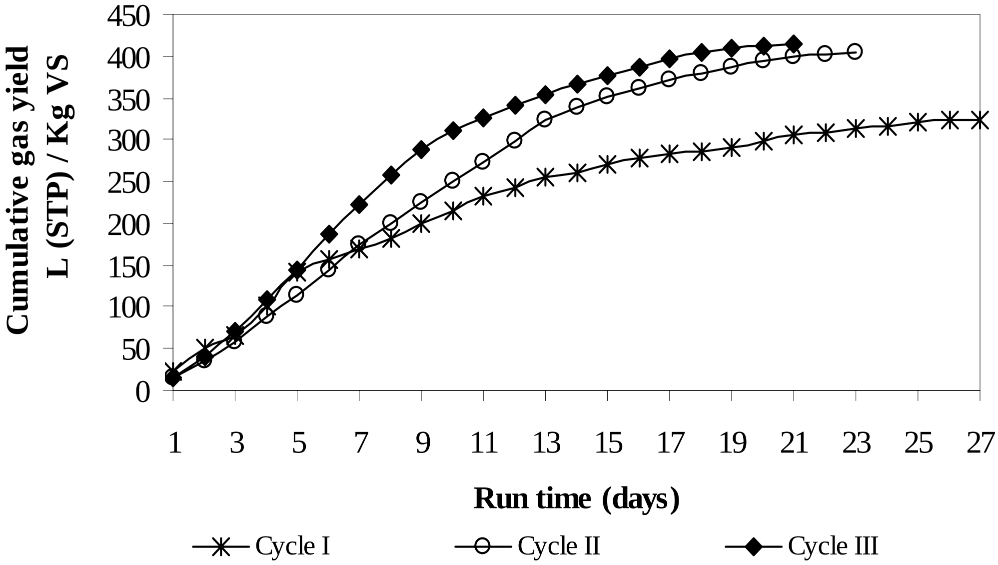


Figure 4.25: Specific gas production in each cycle

It is reasonable to normalize the gas yield by total volatile solid (VS) as solid waste characteristics differ and therefore the loads. Figure 4.25 presents cumulative gas production normalized by VS content in the waste. Cycle II and III not only produced higher biogas but also did so in shorter digestion period. Cycle III completed in 21 days with gas yield of 417 L/kg VS. However, during the same period, cumulative gas yields were 305 and 400 L/kg VS for cycle I and II, respectively. The first cycle was perhaps not as efficient as the subsequent cycles. Further, the curves in Figure 4.25 could have resulted from different cross-circulation rate as a primary determinant of waste stabilization. Therefore, these experiments showed that, within the flushing volume reported here, the degradation is a function of both kinetics and flushing rate. The experiments here demonstrated a higher degree of solubilization and mobilization with the increased recirculation. The flushing of a fresh waste rector with the leachate from a stabilized waste reactor during sequencing not only provide inoculum containing acid formers and methane formers but also provided a suitable pH environment favorable for the growth of microorganisms. Moreover, increased flow may lead to less chance of short-circuiting thus providing more efficient inoculum distribution. Higher circulation rate also improves the inoculation of fresh reactor, allowing it to reach balanced condition quickly. This finding is in line with findings of Chug et al. (1998) who observed better digester performance, in terms of gas yield and digestion period, with higher recirculation rates.

Figures 4.26 present specific methane yield in three SEBAC cycles. The specific biogas yield, methane yield in particular, increased considerably from cycle I to cycle II but only a slight increment was noticed in cycle III. Besides gas yield, the digestion time also shortened as illustrated in Figure 4.27. The specific methane yield obtained was 184, 217 and 240 L CH_4 /kg VS, respectively. This value of methane yield is one and half times higher than the yield reported by Chug et al. (1998). This values corresponds to the 63 %, 74 %, 82 % process efficiency calculated based on the laboratory BMP assay (293.82 L/kg VS at STP). Volatile solid reduction was observed in cycle III (80%) also found slightly higher compared to 78 and 79 % in cycle I and II respectively (Table E-1).

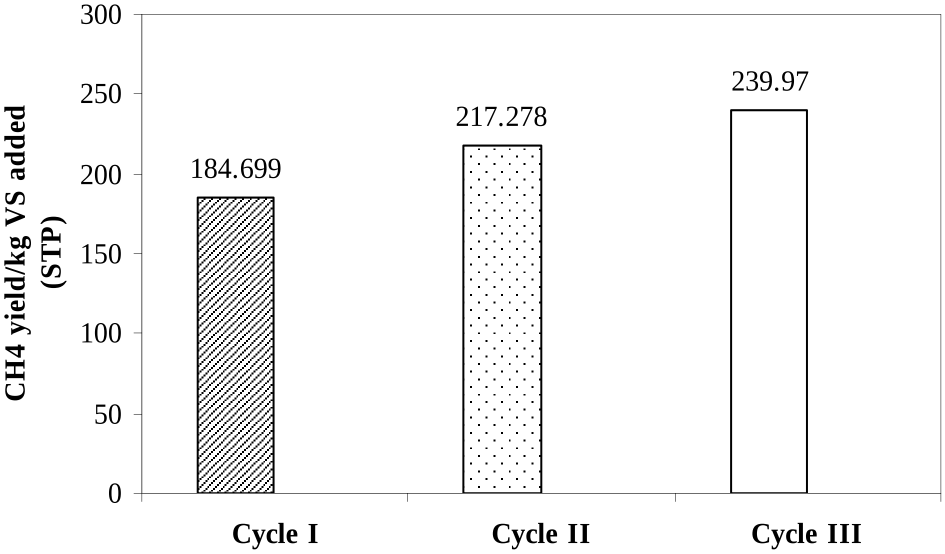


Figure 4.26: Specific methane production in each cycle

Overall SEBAC assessment results are summarized in Table 4.2. The early start-up of methanogenesis and increased methane production rates at higher flows could be due to the increased flushing and dilution of the inhibitory products, maintenance of favorable environmental condition and providing higher quantities and concentration of inoculum. Although these experiments show the rate and extend of waste decomposition improved with increase in moisture flow, the maximum volume of the leachate that can be recirculated depends upon the volume remained in the stabilized reactor after digestion completion (settlements) as well as how much load it can take. This means that the precautions has to be taken if the pH of the effluent leachate from stabilized waste reactor if began to drop continuously due to increased loading after sequencing commenced. However, such situation was not experienced in these experiments.

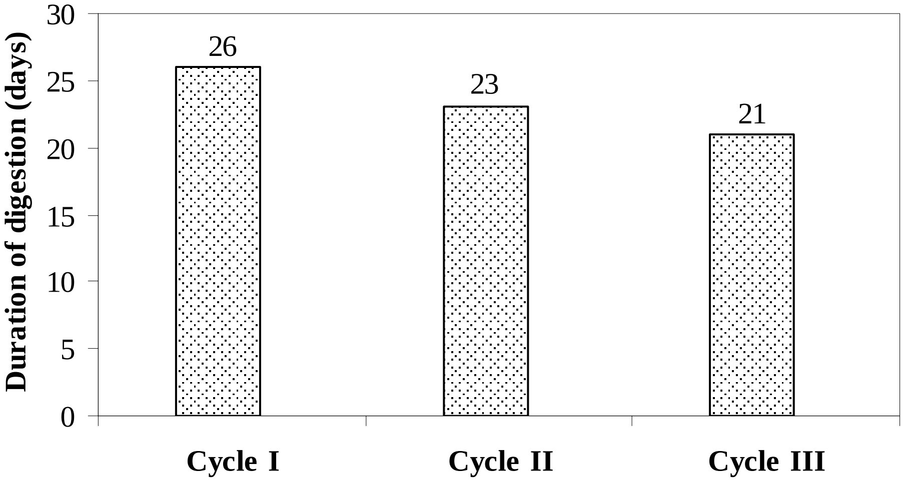


Figure 4.27: Duration of digestion time in each cycle

Table 4.2: Overall SEBAC process assessments

Parameters	Units	Run 1	Cycle I	Cycle II	Cycle III
Total volume biogas production	(L)[1]	7225.97	5927.17	6669.07	7762.81
Total volume of methane production	(L)[1]	3956.52	3380.33	3672.35	4439.49
Biogas production /Kg VS Input	(L)[1]	257.15	325.66	394.61	417.35
CH_4 /Kg VS in pilot scale experiments	(L)[1]	140.83	184.94	217.94	239.97
CH_4 /Kg VS in Lab BMP assay	(L)[1]	293.82			
Process efficiency	(%)	48.61	62.94	74.18	81.67

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

4.2 Continuous Anaerobic Digestion

4.2.1 Feedstock characteristics

For the continuous anaerobic digestion, solid waste was collected from Taklong municipality dumpsite. Feedstock was shredded to average size of about 10 mm. Enough feedstock to last for at least two weeks was prepared and stored at a temperature of 4 °C The frozen waste was thawed to room temperature for 2-3 hours before feeding to a reactor to avoid temperature shock to the microorganism. Analysis of feed stock samples was carried out for every collection in duplicate and results are presented in Table 4.3 as average values.

Table 4.3: Feedstock characterization for continuous reactor

Feeding	Moisture content (% MC)	Total solid (% TS)	Total volatile solids (% TVS)	Non-volatile solids (% inert materials)
Inoculum	93.927	6.07	13.60	86.40
Feedstock waste	88.5-90.5	9.5-11.5	72.4-79.5	27.6 – 20.5

4.2.2 Initial phase: Start-up and batch feeding

For the start-up of the digestion process, the digester was fed with 90 kg feed, to which 20 L of inoculum (8 kg cow dung, 6 kg of anaerobic sludge and 6 L of water) was added. At this stage, the total feed intake was 50% of the reactor volume. It is noted that the inoculum was acclimatized in 55°C for 4 weeks. Only when acclimatized inoculum produced negligible biogas, was it mixed with the waste in the reactor. Mixing is important in anaerobic digestion to ensure that conditions are consistent throughout the digester and bacteria have rapid access to digestible surfaces. Mixing in the reactor in this experiment was carried out through leachate percolation at the rate of 200 mL/ min for 3 hours daily. Performance parameters like pH, alkalinity, VFA, biogas production and composition, etc. were monitored everyday.

As mentioned elsewhere, no feed was applied to the digester for the first 2 weeks as biogas production was increasing. Only when a significant drop in biogas production was observed, feedings were resumed on day 19, at the rate of 3 kg of solid waste per day. This was continued until it reached the full working capacity.

1. Leachate characteristics

Organic content in the leachate can be measured by Chemical oxygen demand (COD) or total organic carbon (TOC), TCOD, SCOD and Dissolved total organic carbon DOC were monitored for 2 weeks (Appendix -Da). Figure 4.28 presents the daily variation of TCOD, SCOD and DOC in leachate. The significant increase in COD in leachate is an indication of an active hydrolysis phase. Comparing concentration of total COD and soluble COD, it is seen that soluble organic accounts for the major fraction of total organic leached from the waste. COD and DOC concentration started to increase and reached maximum on day 10 before starting to decrease thereafter. Ghanem et al. (2001) based on their work on kitchen waste, reported that COD of leaching reached maximum on day 10. When concentration of COD increased, increase in DOC concentration was also observed. This showed that there exits a valid relationship (ratio) between these two parameters. Therefore, DOC can be taken as a meaningful parameter in the evaluation. Accordingly it was monitored for the rest of digestion process.

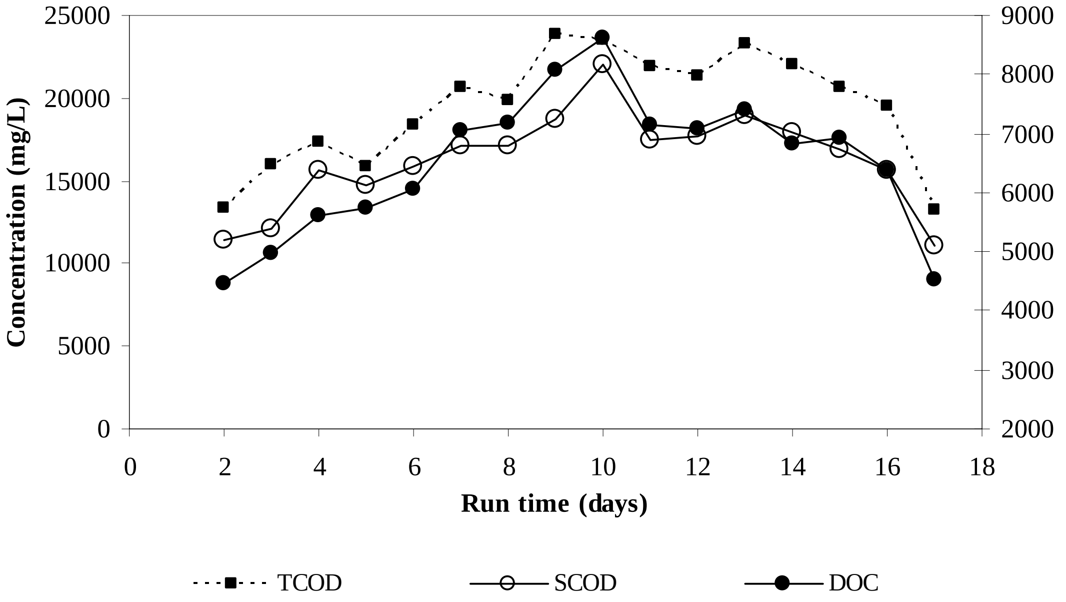


Figure 4. 28: Variation in TCOD, SCOD and DOC

pH and VFA and DOC changes in leachate from pilot scale continuous reactor are shown in Figure 4.29. The pH value dropped from 6.8 to 6.2 during the first five days of operation, meanwhile, the VFA and DOC concentrations increased to their peak values Concentration of TVFA in the reactor began to decrease from 4900 mg /L to as low as 1600 mg /L which led to pH increase from 6.2 to 7.8 (day 17). The pH of leachate stabilized in the range of 7.5 ± 8.0 then after. Interestingly, volatile fatty acids (VFA) content, which increased at the beginning reaching the maximum value of 4900 mg/L, dropped significantly to 1600 mg/l within the next 5 days. The VFA remained constant within a close range. This indicates that there is no imbalance situation.

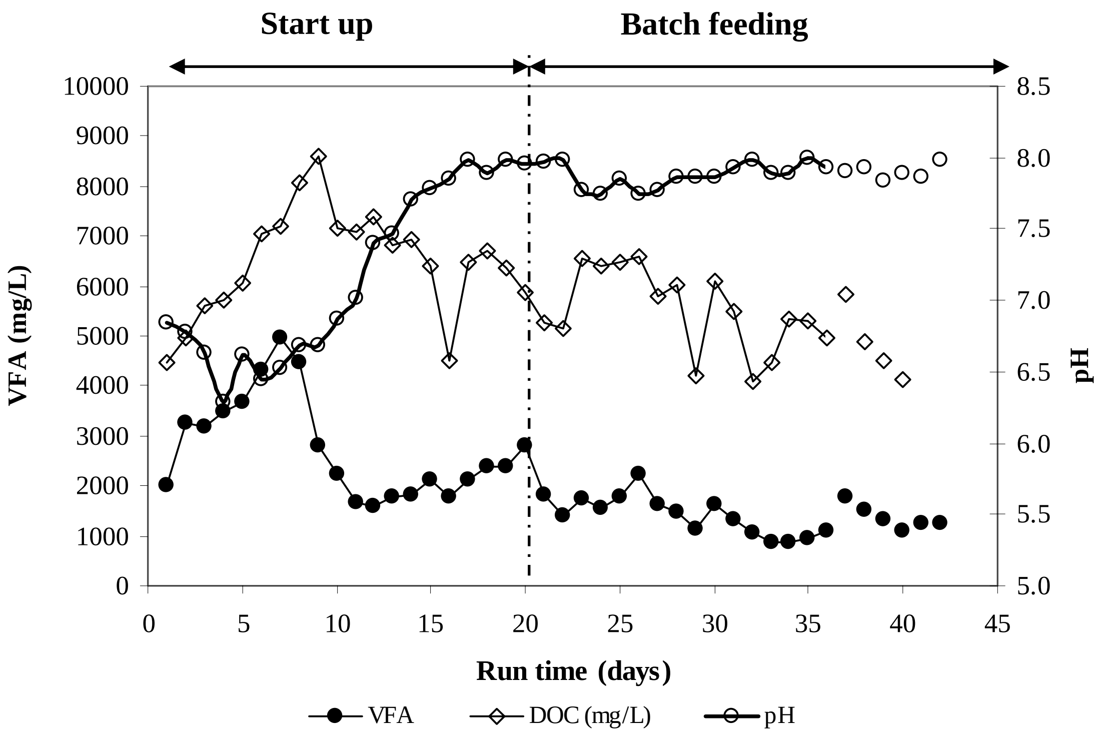


Figure 4.29: Variation in VFA, DOC and pH

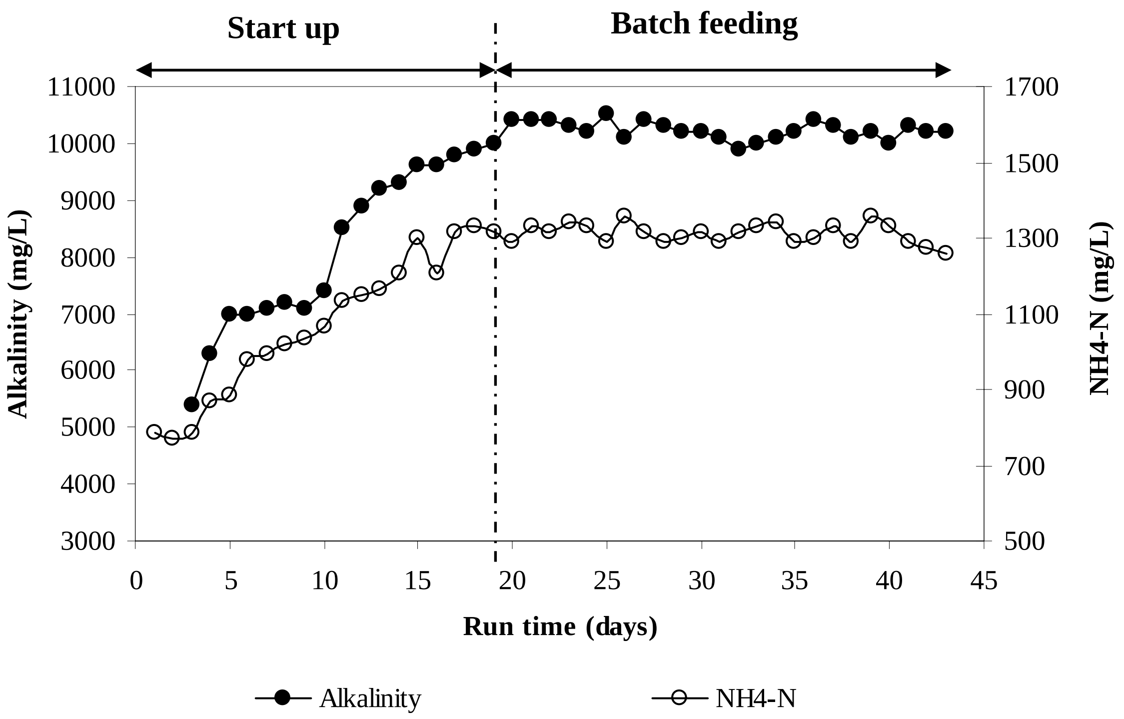


Figure 4.30: Variation in Alkalinity, and NH_4-N

Alkalinity and NH_4-N which gradually increased during the first phase of operation, stabilized in a narrow range. The alkalinity increased from 5000 mg/L to 10000 mg/L before arriving at a relatively stable concentration. Likewise, NH_4-N also exhibited similar trend increasing from 780 mg/L to 1300 mg/L which is well below the inhibitory concentration level as illustrated in Figure 4.30. The increase in alkalinity is attributed to degradation of protein present in the waste. The degradation releases NH_3 which reacts with CO_2 forming ammonium carbonate as alkalinity.

2. Biogas production

The volume, rate and composition of the biogas produced are indicative of digester performance. In the first 2 weeks, no feed was applied to the digester as biogas production was increasing. Biogas composition reached 50% methane concentration at day 10 and reached a maximum value of 65% at day 15. During the second phase of operation, the methane concentration relatively stabilized with values slightly fluctuating in the range of 58 to 62% as presented in Figure 4.31.

Biogas production varied in a wide range. In fact daily biogas production was not uniform. (Appendix D-1).This daily variation is clearly seen in Figure 4.32. Daily biogas production as high as 270 L/day (57 L/kgVS.day) was recorded where as 89 L/day (13.9L/kgVS.day) was observed on day19. Although the daily gas production does not show any trend, it can be clearly observed that at day 19, the production nose dived. It is argued here that the system might have been running under substrate deficit condition, and therefore, feeding was resumed at the rate of 3 kg per day (0.25 kgVS/day). During the second phase of operation (batch feeding), daily gas production started to increase. This phase was marked by a relatively stable daily gas production with 100 L/day (362.3 L/kg VS $_{input}$. day). In order to better observe the performance of the digester, accumulative gas production is also drawn (Fig 4.32). Accumulative gas production is especially meaningful because it provides clear increasing trend with the run time. Despite daily variation in gas production, accumulative gas production line shows uniform straight line pattern indicating good performance of the reactor.

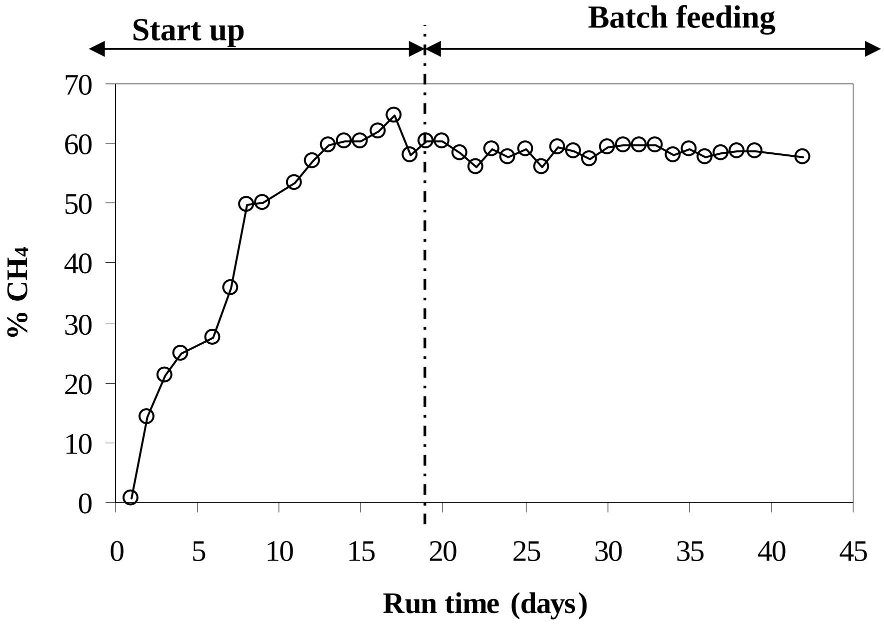


Figure 4.31: Change in concentration of CH_4 in biogas during initial phases of operation

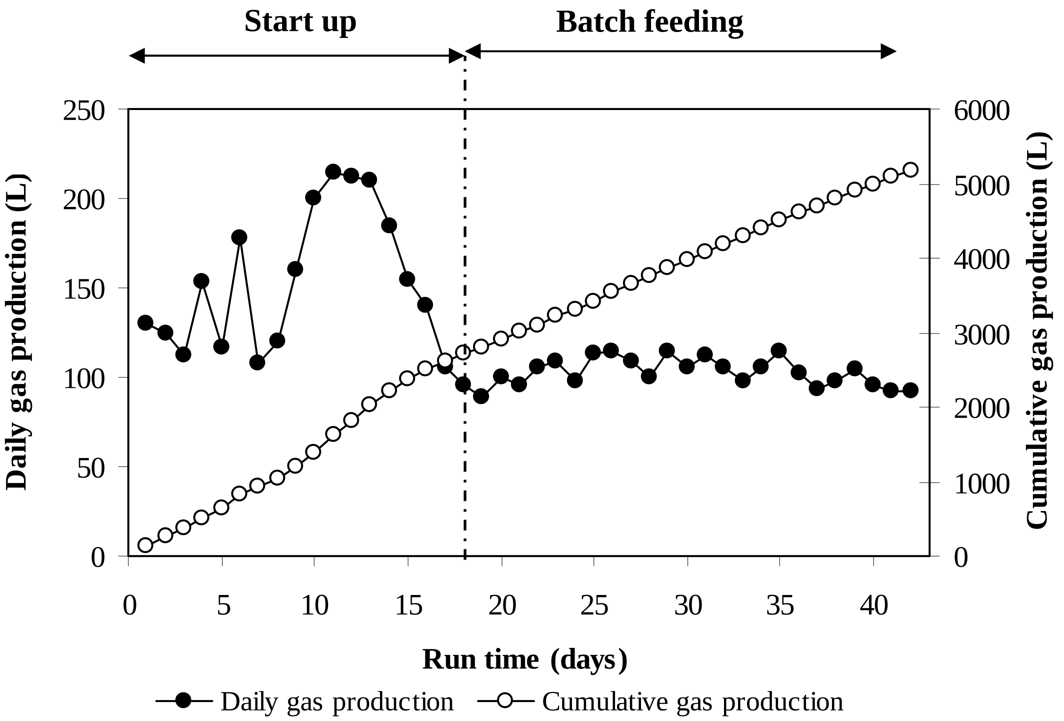


Figure 4.32: Daily and accumulative biogas production during initial phases of operation

4.2.3 Final phase: Continuous operation

This is the final and continuous phase of operation. During this process, feeding was continued but with an increasing rate. The reactor was fed with the initial loading rate of 5 kg/day (0.46 kgVS/day) in a draw-and-fill mode. This loading rate was higher than the rate of loading during the batch feeding. The loading rates were gradually increased and digester was operated for the period as shown in the Table 4.4. The digester was operated for the period equal to the mass retention time, at the minimum. The mass retention time is defined as the ratio of average reactor wet mass content/wet feed rate. (Valdez-Vazquez et al. 2005; Oleszkiewich et al.1997, Kayhanian & Tchobanoglous, 1993).The initial organic loading rate (5 kg/day) translates into a mass retention time of 32 days as the total mass in the reactor is estimated to be 160 kg. The working volume of the digester was approximately maintained below 80% of the total digester volume. Loading (feeding) and unloading (withdrawal) was done with proper mass balance equation as described in chapter 3 section 3.3.3. Once the reactor is operated for the required number of days as determined from the mass retention time another loading rate was started. Four such loading rates were used as shown in the table below (Table 4.4).

Table 4.4: Loading conditions for continuous operation

Loadings descriptions	Loading Rate(kg/day)	Loading Rate(kg VS/day)	Mass retention time (Operation days)	Operation Mode
Batch feeding	3	0.25	-	Feeding only
Loading 1	5	0. 46	32 days (32)	Draw-fill
Loading 2	7	0.64	22 days (22)	Draw-fill
Loading 3	9	0.84	18 days (18)	Draw-fill
Loading 4	11	1.02	12 days (21)	Draw-fill

1. Leachate Characteristics

The pH of effluent leachate from the continuous digester (Figure 4.33) remained steady state to the range of 7.5-8.0 during the first three feeding rates of 5 kg, 7 kg, and 9 kg per day. When the loading rate was increased to 11 kg/day (1.02 kg VS/day), the pH value dropped from to 7.3 (Appendix-Db). Because the pH is controlled by the volatile organic acid concentration, the alkalinity showed similar trends. Although the pH value was still above 7 which is the methogenic growth range, the methane content in the biogas dropped and system showed preliminary signs of overloading. The digester was unfed for 4 days before the system could recover. Loading was resumed at the same rate of 1.02 kg VS /day.

Leachate characteristics under investigation were DOC, VFA, pH and Alkalinity. Figure 4.34 shows daily variation of DOC and VFA during different loading rates as marked by loadings 1, 2, 3 and 4. During the first two organic loading rates, (0.5 kg VS and 0.64 kg VS), DOC remained steady state with most of the records fluctuating in the range of 6000 mg/L to 7000 mg/L. While VFA value was fluctuating between 4000-5000 mg/L. Accumulation of VFA was not significant to cause the instability of the process as all performance parameters were doing well. This, however, when the feeding was increased to 9 kg/day that translates to organic loading of 0.8 kg VS/day, both parameters showed increasing trends. As biogas production was increasing, VFA was being consumed rapidly, converting it to methane and carbon dioxide. The DOC consistently increased to 9000 mg/L when the waste feeding was increased to 11 kg/day. The concentration of DOC and VFA followed similar pattern and were almost parallel during the same period. It indicates that most of DOC is contributed to the volatile organic acids. As the fresh feed increased, it generated more VFA than it could be consumed by the microorganisms, and therefore accumulation increased. On day 122, the highest VFA value of 7543 mg/L was observed accompanied by a slight drop in pH. However, it showed a decreasing trend onwards. The recovery of the system may be attributed to the higher alkalinity (above 8000 mg/L) which provided buffering to keep the pH around neutral value as well as precaution taken as mentioned earlier.

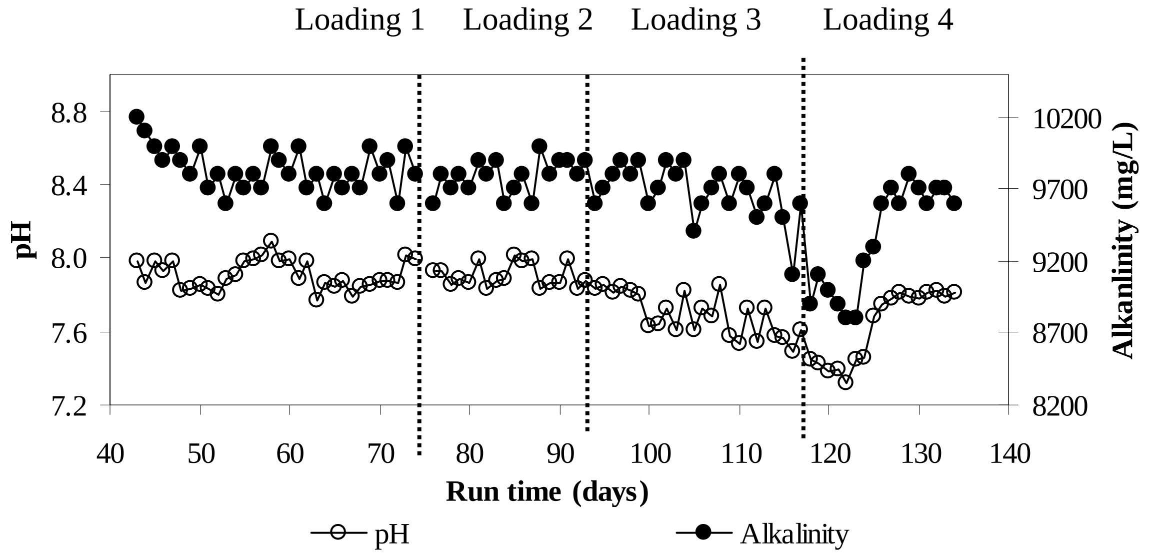


Figure 4.33: Variations of pH and Alkalinity

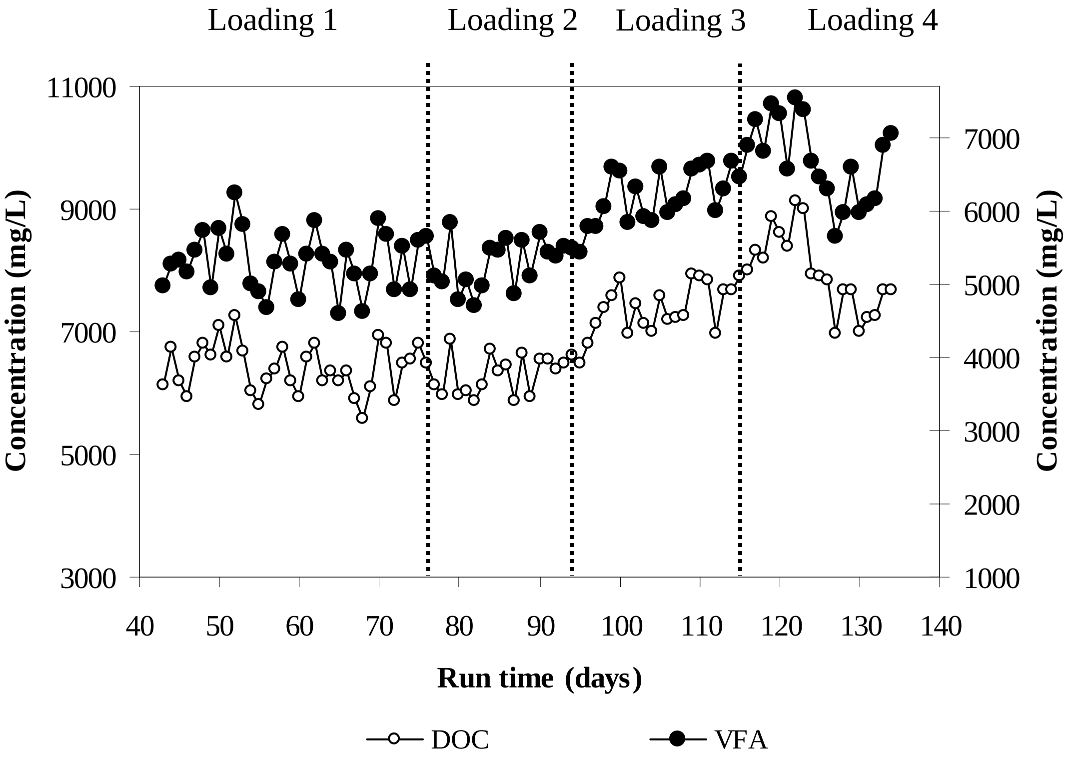


Figure 4.34: Variations of DOC and VFA

Ammonia (NH_3) is one of the hydrolysis products formed during the degradation of protein. NH_4 exits in two forms: ammonium ion and free ammonia. The relative concentration of free ammonia and ionized ammonia are dictated by the system pH. At high pH value (>8), unionized (free) form dominates, which is more inhibitory to methanogens. Results on investigation of the ammonium inhibition level are conflicting and have been obtained under different conditions, such as pH, temperature (Borja et al, 1996). However, in this study, pH remained below 8, and ammonium nitrogen did not appear inhibitory at the level of 1626 mg/L though inhibition above 1500 mg/L has been reported in WPCF (1987). Adaptation of methanogens to high concentration of ammonia could have increased the tolerance to microbes. Acclimatization is another factor that influences the degree of ammonia inhibition (Sung & Liu, 2003). Poggi et al. (1991) reported successful acclimatization at the concentration above 5000mg/L.

With the increase in mass loading, increasing trend in ammonia concentration was noted as depicted in Figure 4.35. This correlation, however, is not strong for loading 3 and 4. It is noted here that, higher loads are not necessarily conducive of higher total ammonium levels (Oleszkiewicz & Poggi-Varaldo, 1997). pH dependent presence of unionized ammonium might have been mitigated by the generation of VFA at higher loading.

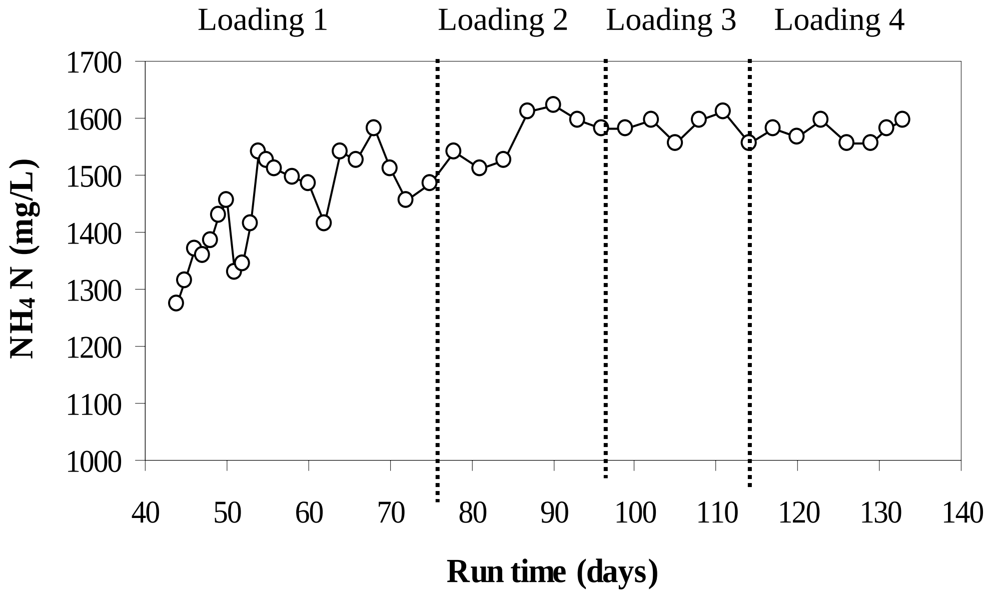


Figure 4.35: Tends of NH_4 Nitrogen during the operation

2. Biogas production

Daily biogas production and composition monitored (Appendix D-2).The measurements of the quantity and composition of the biogas produced, in terms of methane and carbon dioxide content is of fundamental importance to evaluate the stability of the process. As carbon dioxide content in the biogas was found increasing means that the acidifying microorganisms are prevailing on the methanogens that may lead to VFA accumulation. Figure 4.36 displays daily and cumulative biogas production during different loading rates. Increase in daily biogas production was observed with the increasing organic loading rate as indicated by the increase gradient of the cumulative biogas production line.

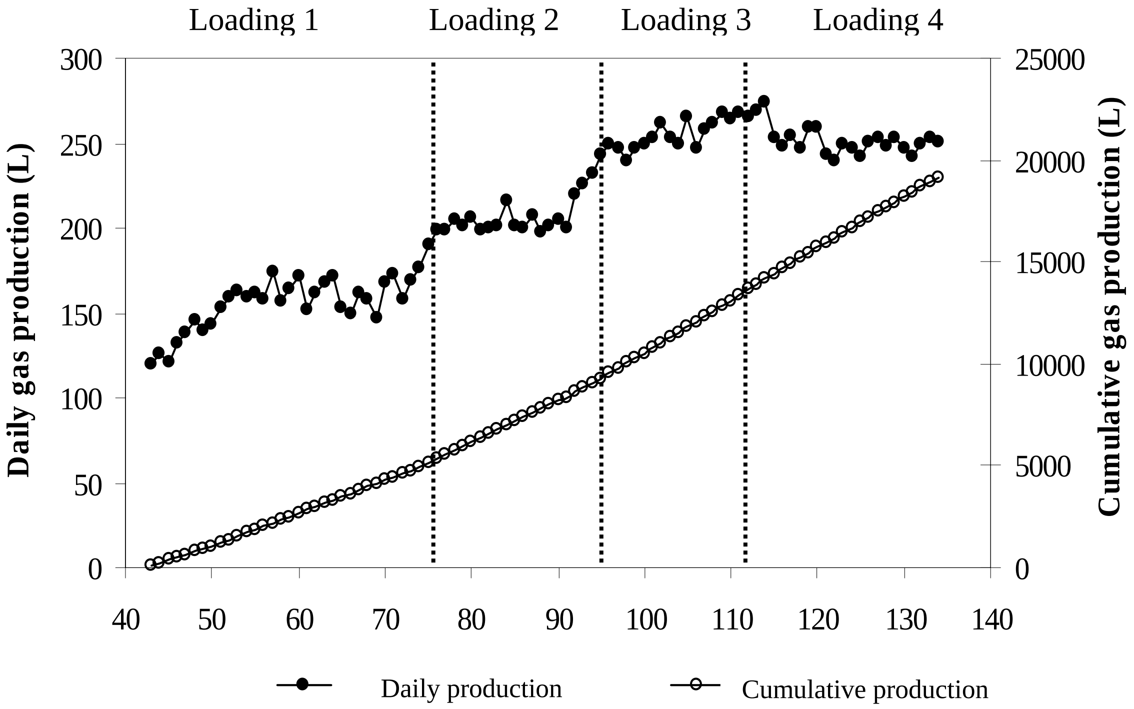


Figure 4.36: Daily and accumulative gas production during continuous phase

Methane concentration was observed mostly above 50% of the biogas produced for the loading rates of 5 kg, 7 kg, and 9 kg per day (Figure 4.37). However, a few days after the loading rate was increased to 11 kg (1.02 kg VS), the composition of biogas showed methane content dropping below 50 % marginal level (around 47%). Interesting co-relation between methane concentration in the biogas and biogas production rate was observed. When concentration of methane in biogas was low, a decrease in daily gas production was noticed (See Figures 4.36 and 4.37).

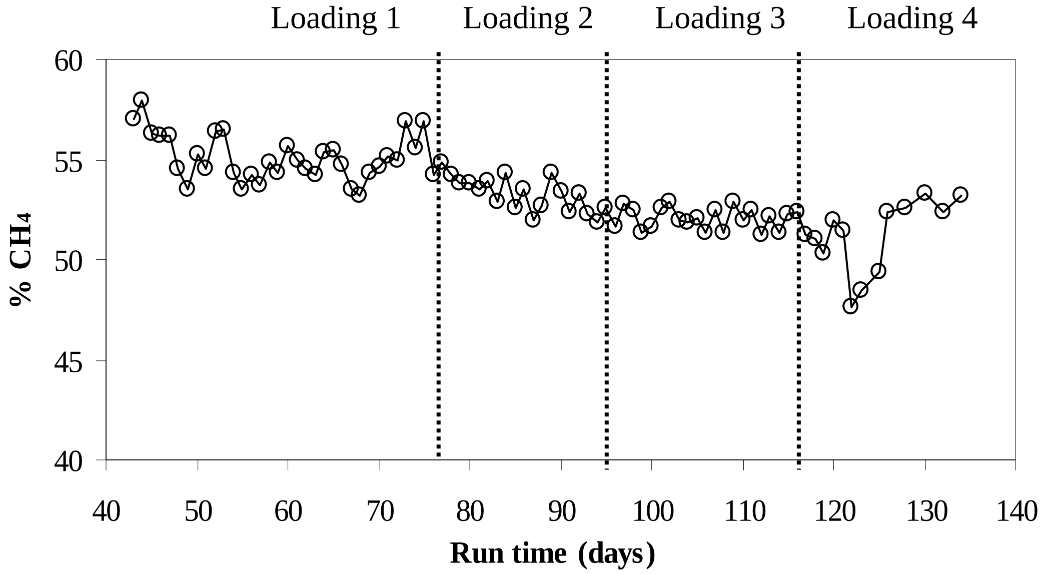


Figure 4.37: Trends in biogas composition during continuous operation

The decrease in biogas generation and deteriorating biogas composition along with the drop in pH as mentioned earlier, were the indicative of the system possibly approaching to the overloading.

4.2.4 Continuous process assessment

Continuous anaerobic digester as designed and operated in the research is simple yet the process within the reactor is complex. It is difficult to divide the process according to the loading rate and assess each rate in terms of biogas yield, the quality as well as the quantity. This is because the biogas generated can not possibly be directly linked to feed waste being loaded on that day. The reactor is a complex black box (closed system) operating different stages of fermentation at a given time. However, for the sole purpose of assessing the effect of loading rate upon the system, once the biogas generation peaks up and stabilizes for each loading condition, the steady state results are taken. Figure 4.38 presents gas production rate for four different loading conditions. The highest biogas production 1.07 L/day per unit waste volume was obtained for loading 3 (0.84 kg VS/day) whereas slightly lower value (1.04 L/day per unit waste volume) was obtained for loading 4 despite having higher organic loading rate of 1.02 kg VS/day. This finding is in close agreement with Castillo et al. (2005) who reported increased gas production rate with decreased retention time.

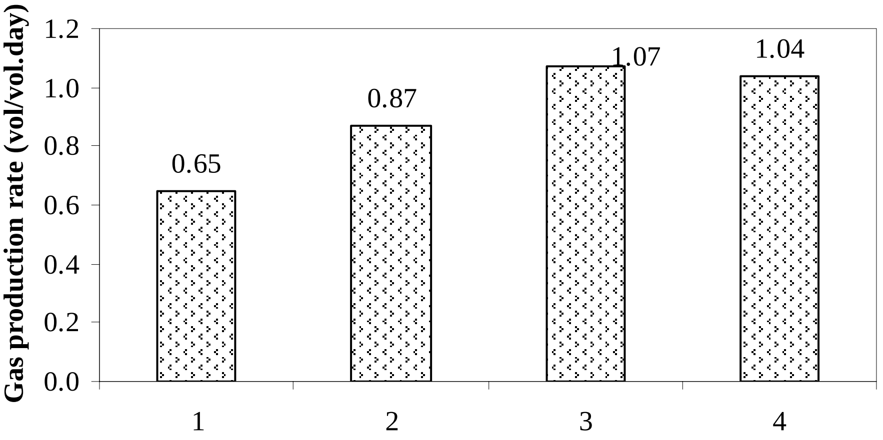


Figure 4.38: Gas production rate for various loading rates

Accordingly, Figure 4.39 is presented which shows the accumulative biogas yield at different loading conditions. With gradual increase in loading rates from 5 kg/day (loading 1), to 7 kg/day (loading 2), and 9 kg/day (Loading 3), the cumulative gas production has increased too. However, at the organic loading rate of 11 kg/day which amounts to 1.02 kg VS/day, the cumulative biogas production did not show any increment, the accumulative gas yield slightly dropped as shown by the slope of the loading 4 line in Figure 4.39.

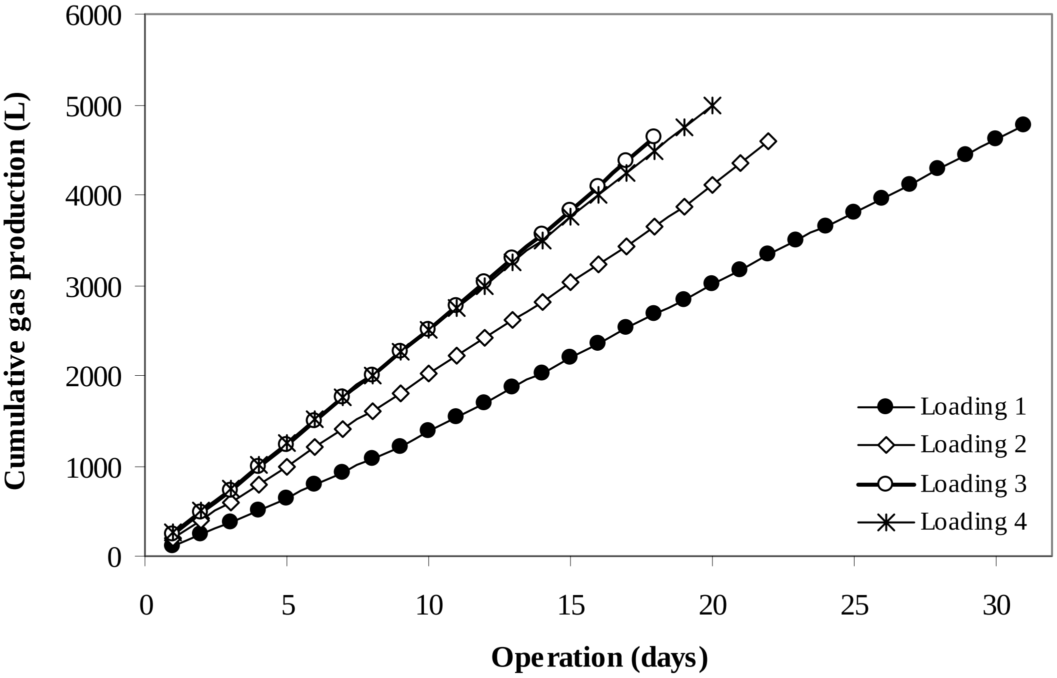


Figure 4.39: Cumulative gas yield for different loading conditions

To further the investigation, specific gas production for various loading rates is plotted and presented in Figure 4.40. The highest specific gas production observed was 335 L/kgVS in loading 1 (1.9 kg VS/m^{3}day). As the loading was increased, a gradual increase in the amount of biogas production (L/day) was observed, accompanied by a decrease in the yield of biogas (L/kgVS). This result is in line with the findings reported by Castillo et al. (2005). However, for the organic loading rate of 11 kg/day (loading 4), significant drop in specific gas production is noticed. Although the organic loading was increased, the gas production rate and specific gas production did not increase.

The loading rate (3.5 kg TVS/m^3.day) reported here should be interpreted in line with Mata-Alvarez et al. (1992) who mentioned that higher biodegradability of the wastes means larger and faster VFA production which stress the validity of the organic loading rate (OLR) limit. It should be cautioned here that the optimum loading rate of 3.5 kg VS/ m^{3}day observed here is not universal and the optimal rate depends upon the reactor configuration (Cecchi et al. 2003). For a continuously stirred tank reactor (CSTR), overloading of digester above 4 kg TVS/m^{3}day was reported by Lane (1984). The overloading was marked by the fall in pH and gas yield and an increase in the carbon dioxide content in the biogas. Bouallagui et al. (2003) obtained the best results with an organic loading rate of 2.8 kg TVS/m^3.day. Organic loading rate as high as 10-18 kg TVS/m^3 day was quoted in some commercial literature but direct comparison is difficult as commercial literature cites the best case studies after long operation period and often does not specify detail procedure (Oleszkiewicz et al., 1997).

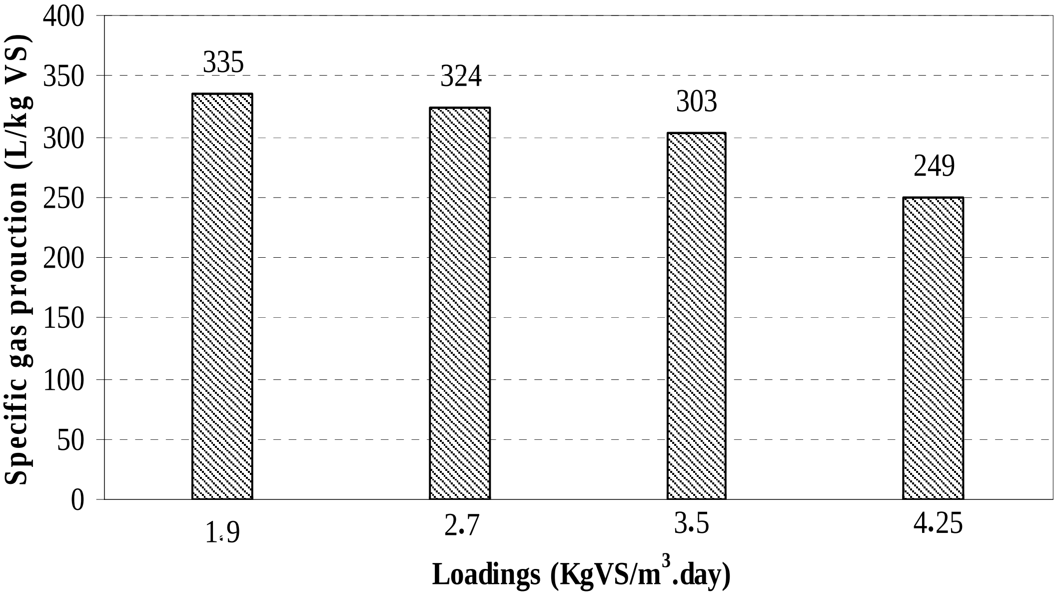


Figure 4.40: Specific gas production for various loading rates

4.3 Bio-chemical Methane Potential

Bio-chemical Methane Potential (BMP) assay is a rapid and inexpensive method to determine methane yield. BMP test is the key criteria used to evaluate the performance of the anaerobic digestion process and measures the anaerobic biodegradability of substrates.

Bio-chemical Methane Potential (BMP) tests were performed on substrates at thermophilic temperature (55°C). Detailed procedure is presented in chapter 3.4.1.The tests were conducted on blank and substrates (OFMSW). All tests were conducted in duplicates and the highest value obtained from the test is reported in the result (Appendix F-1). Figure 4.41 displays the methane potential of the substrates and the blank reactor. The blank sample which includes water and inoculum represent the gas production produced by the inoculum itself. The methane production from the inoculum was subtracted from methane production of the waste samples to get the corrected value of methane potential. The volumes are all converted to standard temperature and pressure (STP) conditions. It is concluded from the Figure 4.41 that methane potential increased rapidly and stabilized at day 50. This is in line with Hansen et al. (2004) who reported that full biodegradation of organic matter is 50 days at thermophilic and 100 days in mesophilic condition. Figure 4.42 Illustrates the corrected methane production generated by the waste sample in terms of CH_4 L/kg VS at STP. Thermophilic incubation showed that for each kg of VS of OFMSW, 293 L of methane could be produced.

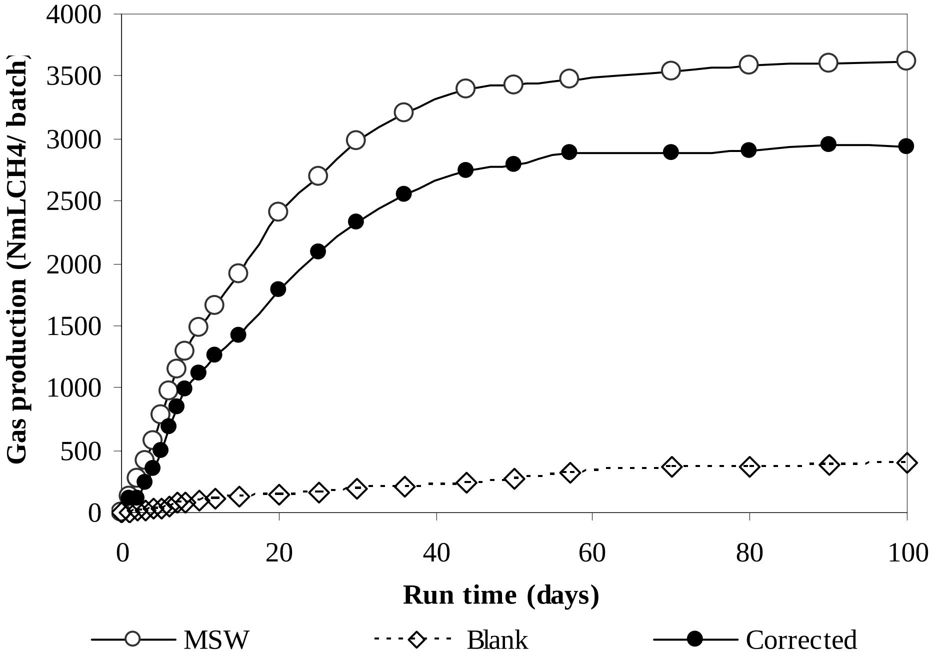


Figure 4.41: Cumulative methane production at STP

Juanga (2004) conducted BMP tests on various substrates under mesophilic incubation and reported that fresh market waste has the highest methane potential of 400 L / kg VS. For OFMSW, the potential volume was found to be 300 L/kg VS which is similar to the result obtained in this research.

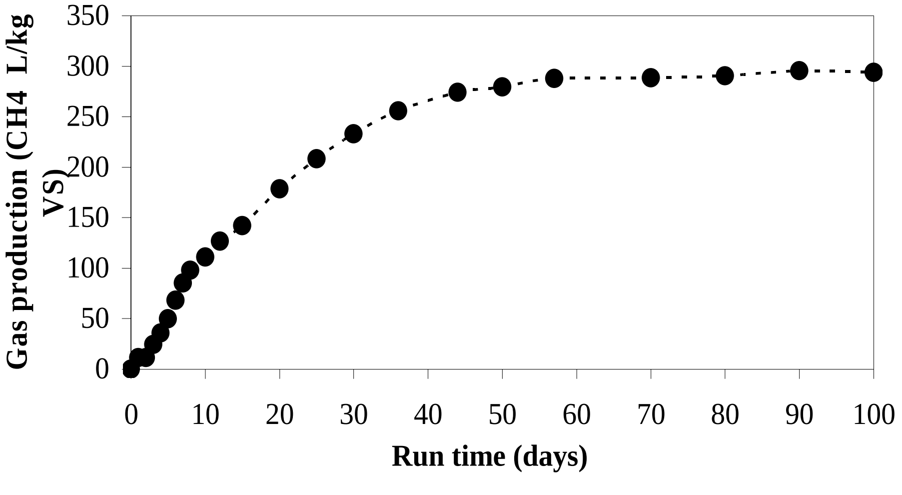


Figure 4.42: Corrected cumulative methane production at STP

4.4 Digestate quality

The digested, although fairly stable, requires post-curing if certain standard has to be met (Oleszkiewicz et al., 1997). This is commensurate with the findings of Kayhanian and Tchobanoglous (1993), who demonstrated no odor in the finished products after the anaerobic-aerobic sequence. The digested from both operations, batch and continuous digestions, were tested for nutrient values for agricultural purposes. It is noted here that digested waste form batch process was cured for 2 weeks. Digested from continuous digester was cured after dewatering in the sand bed. The reason for that is to allow the aerobic degradation because lignin (fibers) is not degraded in anaerobic digestion. The fibers are degraded by fungi. Many fungus fruiting bodies and mycelium were seen growing in the heap during curing.

Physical, chemical and biological characteristics of the final product are required to be analyzed, to be used as soil-conditioner. One of the main concerns in the analysis is the pathogen. Since the operation was on thermophilic temperature (55°C), there is higher chance of pathogen reduction. Theomorphic operation (54-58°C) ensures the elimination of most pathogens (Kayhanian & Tchobanoglous, 1993). Another important criterion is the concentration of heavy metal. Table 4.5 shows nitrogen and phosphorus content along with heavy metal concentration in the digestate. Based on analysis results obtained from the laboratory investigation, there is very little cause of concern from heavy metal contamination. This could be because the feedstock waste was hand-sorted and clean. All heavy metal concentration fell below the WHO standard (proposed, 1997) of compost for developing countries. The percentage of nitrogen and phosphorus in the digestate as obtained shows that anaerobic digestion does not reduce nitrogen and phosphorus but keeps the value of nutrients intact for fertilizer.

The nutrient characteristics have a great influence on the application of material for the agricultural use. Major elements used to evaluate the suitability of compost for agricultural usage include Nitrogen (N), Phosphorus (P) and Potassium (K). Another important nutrient characteristic is the C/N ratio. All the nutrients analyzed in this study were within the Thai guideline to be used as organic fertilizer as presented in Table 4.6. Alternatively, calorific value analysis showed that the final humus produced being rich in fibers, it can be fired directly in a boiler by mixing it with other fuels or palletized as a fuel source. Calorific values of digested from batch and continuous digestion were 13.8 and 14.01 MJ/kg respectively. The values obtained in this research showed a close agreement with Kayhanian & Tchobanoglous (1993) who reported the energy content of 14 MJ/kg from humus obtained after anaerobic digestion of biodegradable fraction of municipal solid waste followed by aerobic bio-drying.

Table 4.5: Heavy metal analysis of digestate

	Heavy metals (mg/kg DM)						
	Cd	Cr	Cu	Pb	Ni	Zn	Mn
WHO standard (proposed)	3	50	80	150	50	300	-
Batch	0.85	14.5	40	26.2	9.75	119	109
Continuous	0.45	5	50	3.2	12.5	55.5	85
*France	2	150	100	100	50	300	

Table 4.6: Nutrients analysis of digestate

	pH	Nutrients				C/N ratio	Calorific
		N (%)	P (%)	K (%)	TOC (%)		
Batch	7.05	2.26	0.57	0.6	24.06	10.64	13.81
Continuous	6.99	2.17	0.68	0.6	26.66	12.28	14.01
Thai guideline**	6-7.5	1.0	1.0	0.5	-	< 20	-

*Rattanaoudom, 2005 cited Source: Compost -Consulting development, 2004
**Rattanaoudom, 2005, cited Source: Land development department

4.5 Energy Balance

4.5.1 Energy Balance in SEBAC

Both SEBAC and continuous anaerobic digestion process consume energy at various stages of operation from feedstock preparation to heating, pumping and process operation. Therefore, the total energy production from digestion, as well as the total energy consumption by the system are required to be assessed for the energy surplus or balance analysis. The objective of this study is to examine the economy of the energy potential. Detailed on energy balance is presented in Appendix B-3. It is worthwhile to mention here that caloric value of the digestate has not been considered in energy balance estimation. Obviously, the inclusion of the calorific value of digestate should increase the total estimate of energy surplus.

Table 4.7: Energy balance analysis

Description	Total VS input (kg)	Total biogas production (L) (50-70% CH_4)	Energy produced (MJ)	Energy consumed (MJ)	Energy gained (MJ)	Energy gained (MJ/kg VS)
cycle I	18.28	4650	97.19	32.58	64.61	3.53
cycle II	16.85	4960	97.39	32.58	64.81	3.85
cycle III	18.50	5513	116.00	32.58	83.42	4.51
SEBAC	53.63	15123	310.57	97.75	212.83	3.97
Continuous	67.00	23800	484.14	122.14	361.85	5.40

Table 4.7 presents energy balance analysis of SEBAC process during three cycles. The amount of energy consumed at various stages of operation is shown in Figure 4.43. By far, the process of shredding consumed two third of the total energy consumption followed by water heating which consumed about 32% of total energy consumed. If the gasoline operated mechanical shredder could be replaced by electric one, significant amount of energy could be saved.

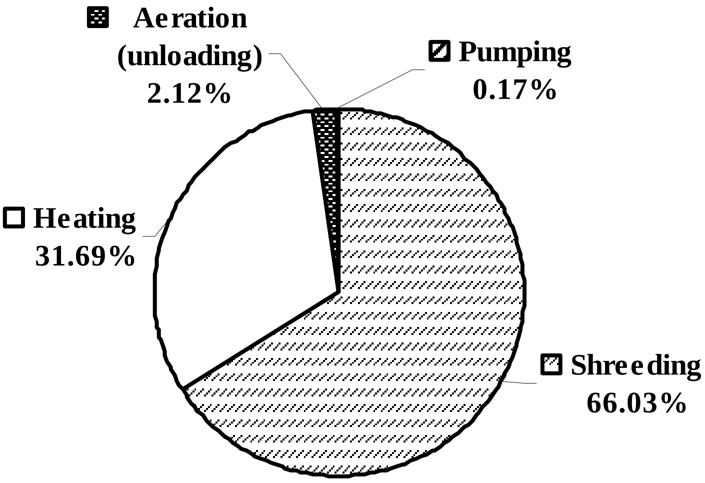


Figure 4.43: Energy consumed by SEBAC

Figure 4.44 shows the energy expended to produce the biogas in percentage. It is interesting to note that even with the mechanical shredding, as much as 66% of surplus energy can be obtained. It can, therefore, be concluded that SEBAC is a net energy gaining system which can produce sufficient amount of surplus energy for the system to be economically viable.

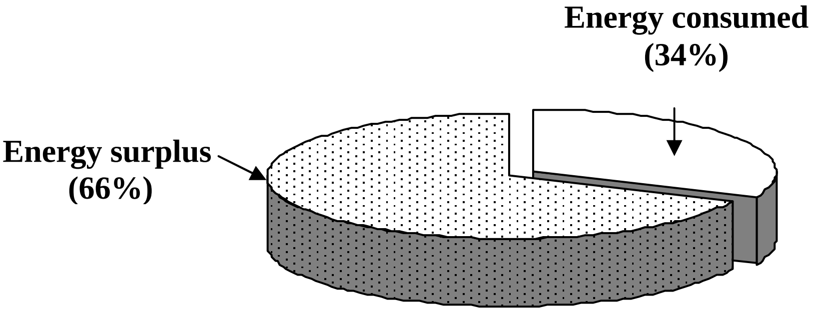


Figure 4.44: Energy balance in SEBAC

4.5.2 Energy balance in continuous digestion

In the continuous anaerobic digestion, shredding accounted for 81% of total energy consumed, the remaining energy being consumed by heating (Figure 4.44). Energy surplus from the continuous digestion was estimated to be 75% as opposed to 66% in SEBAC process. This is obvious as the continuous system did not require energy for aeration and pumping.

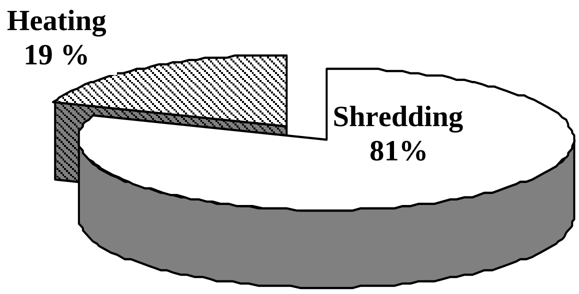


Figure 4.45: Energy consumption in continuous anaerobic digestion

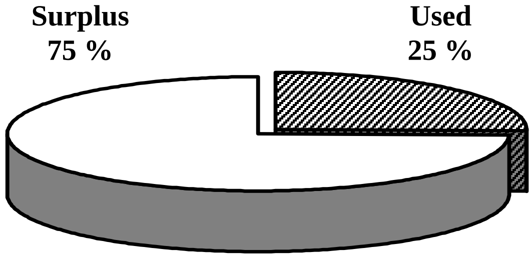


Figure 4.46: Energy balance in continuous digestion

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This study was conducted on anaerobic treatment of OFMSW. SEBAC experiments were conducted in pilot scale reactors. Since a stabilized reactor was used to start up the SEBAC system the need for pre-stage operation was eliminated. Three cycles of SEBAC experiments were performed with different cross circulation rates under thermophilic condition. Higher biogas production in relatively shorter digestion period was obtained under thermophilic condition. A continuous anaerobic digester was designed and operated under thermophilic condition. The following conclusions are drawn based on the observed results.

(a) Sequential Batch Anaerobic Composting (SEBAC)

- The research reaffirms that considerable amount of cumulative pollutant loads in leachate can be removed from three days of pre-stage flushing operation. The flushing mechanism helps enhance acid as well as prevent VFA accumulation.

- Operating temperature and particle size greatly influences the efficiency of pre-stage operation. Three times reduction on particle size (10 mm) under mesophilic condition resulted into 20% higher pollutant load than thermophilic temperature with larger particle size (30 mm).

- Stress situation can be avoided and shock to microbes can be minimized without affecting the gas production if the mesophilic condition is gradually increased to thermophilic temperature. The gradual increment at the rate of 2°C was found satisfactory. The experiments also confirm that long time acclimatization of inoculums can be avoided.

- The daily gas production increases steadily if the temperature is increased from mesophilic to thermophilic condition. Under thermophilic temperature, better results are obtained in terms of methane (CH_4) composition as well. The research, therefore confirms the earlier findings that the biogas production rate in thermophilic temperature is considerably higher since the thermophilic micro-flora have the capacity to use several sources of carbon than the mesophilic micro-flora.

- The specific methane yield as obtained with in three SEBAC cycles are 184, 217 and 239 L CH_4 /kg VS, respectively with the cross circulation rate of 0.34, 0.46 and 0.58 m^3 leachate / m^3 of waste per day, respectively. These values correspond to the 63%, 74%, 82 % process efficiency calculated based on the laboratory BMP assay.

- Higher cross-circulation increases the moisture flow and result into more rapid degradation of waste. This may be due to the fact that at higher flushing volumes

VFAs are removed and distributed more efficiently, producing better contact with microorganisms.

- Higher re-circulation rates not only produce higher biogas but also do so in shorter digestion period.

- Energy balance studies show that despite using mechanical shredder, the SEBAC is by far an energy surplus system with 66% energy gain.

(b) Continuous Anaerobic Digestion

- A simple continuous reactor that operates on draw-feed mode can be effectively used for anaerobic digestion of OFMSW.

- This study finds that as the rate of loading increases, the rate of biogas yield also increases. However, there comes a time when increase in feeding load fails to considerably increase the gas production. The highest biogas production rate of 1.07 L/day per unit waste volume was obtained for the loading rate of 0.84 kg VS/day. When the loading rate was increased to 1.02 kg VS/day, slightly lower biogas production (1.04 L/day per unit waste volume) was observed. Therefore loading rate of 0.84 kg VS/day can be taken as the optimum loading rate for the current reactor configuration.

- The decrease in biogas generation and deteriorating biogas composition along with the drop in pH for the loading rate of 1.02 kg VS/day are the early warning indication of the system possibly approaching to the overloading.

- There exists an interesting co-relation between methane concentration in the biogas and biogas production rate; with the increase in feeding load, gas composition shows better results with higher gas generation rate.

- The specific gas production (L/kg.VS) decreases as the loading increases. That means the amount of gas generated per unit weight of mass decreases as the load increases. The highest specific gas production observed was 335 L/kgVS for the small loading rate of loading of 0.46 kg VS/m^3day. Higher load does not necessarily provide higher process efficiency. However, the drop in specific yield becomes less significant if the loading does not approach its capacity.

- The energy balance studies indicate that although the continuous process as described in this research is a one staged digestion system and it consumes slightly less energy, and results into better energy gain (75%) compared to SEBAC.

(c) Post digestate

- The anaerobic digestion end products are fairly stable residues. The percentage of nitrogen and phosphorus in the digestate shows that anaerobic digestion does not reduce nitrogen and phosphorus but keeps the value of nutrients intact for fertilizer. It meets the Thai guideline proposed by Land Development Department Calorific value analysis showed that it has potential to be used as RDF also.

- Based on results from the laboratory investigation, there is a little cause of concern from heavy metal contamination. All heavy metal concentration fell below the WHO standard (proposed, 1997) of compost for developing countries.

5.2 Recommendations

Both, SEBAC and continuous anaerobic digestion of OFMSW, proved to be viable options not only for mass/volume reduction of the waste but also for production of bio-energy and economic byproducts. However, state of art is still deficient and much remains to be done. As for example, further investigation on the effect of recirculation in SEBAC and improved design/layout of continuous reactors are required. The following recommendations are made for batch and continuous processes, separately.

(a) Batch process

- **Biochemical methane potential**

  Biochemical methane potential assay using the leachate obtained form a stabilized-reactor as substrate could be investigated to confirm whether further degradation was achievable under the experimental conditions.

- **Starting up the first reactor to be used for sequential operation**

  As observed in this study, the mature leachate was noted to contain necessary nutrients, inoculums and buffers. Flushing with mature leachate instead of water may offer positive effects to get stabilized reactor earlier. It may provide a favorable environment to enhance acid production. Leachate thus produced can be stored and feedback to it when it gets matured. In this study, an inoculum equivalent to 15% of the feed VS was used. Higher concentration of inoculum can be investigated for the start-up of the first reactor that may leads to earlier active methane phase.

- **Post treatment**

  The solid residue after digestion is mainly composed of hard to degradable materials which are rich in lignin (fibrous matter). In this study, only a few samples were analyzed for nutrients value and heavy metal contamination. Post digested material to be used as agricultural purpose requires a detailed analysis on quality to get the confidence of the end users.

- **Economic analysis**

  As biogas obtained from the process has high calorific value and preliminary energy balance showed that there will be energy surplus that can be marketed. Detailed economic (cost-benefit) analysis can be conducted. Besides, economic savings that could be achieved from the uses of compost in conjunction with the chemical fertilizer can be added.

- **Heavy Metal Balance**

  A simple balance of heavy metal in the input as well as in the leachate and digestate should be of interest to study the fate of heavy metals during the digestion.

b) Continuous digestion

- **Carbon balance:** A detailed study on carbon distribution should be investigated in order to understand the rate of carbon depletion.
- **Changing the feeding frequency:** Positive effects of feeding of reactor twice as obtained by Castillo et al. (2005) can be tried. Feeding reactor twice a day may decrease the shock caused by a great amount of fresh substrate in the digester. Changing the frequency of feeding may help to obtain a more stable condition and higher feeding can be investigated.
- **Long term operation**: Long term operation of digester in optimum feeding rate to Investigate long term operational and maintenance problems.
- **Reactor configuration modification**: One major problem encountered in the study was the difficulty in withdrawing the digested waste. The reactor used for the continuous digestion of OFMSW in this research represented one-stage vessel in which acidogens and methanogens are together in the same vessel. For highly degradable waste, increasing feeding rate may accelerate acidogenic activity, whereas methanogenic population does not increase its activity to the same extent. This may result into lower efficiency (loading). On the other hand, two-stage process affords more control over the intermediate steps of the digestion process. However, simpler designs and lower investment cost of one stage system from economic point of view can not be neglected. A horizontal tubular digester may be designed to serve the purpose of combined benefits from both one and two stage processes. The tubular digester separates acidogenesis and methogenic longitudinally down the reactor, allowing the reactor to behave as a system of two phases. Thus modification of the digester configuration is recommended that will also make withdraw of digestate easier.
- Organic matter is essentially composed of cellulose, lignin and hemicelluloses which have different intrinsic biodegradability. Investigation on contents of these compounds can be conducted to evaluate maximum theoretical quantity of biodegradable organic matter and stability of the waste in stabilized waste.

References

American Society of Agronomy, Inc. (1982). *Methods of soil analysis* (Part 2). Madison, Wisconsin, USA. ISBN:0-89118-072-9 (pt.2).

Angelidaki, I. & Ahring, B. (1992). Effects of free long-chain fatty acids on thermophilic anaerobic digestion. *Applied Microbiology and Biotechnology*, 37:808-812.

Angelidaki, I. & Sander W. (2004). Assessment of the anaerobic biodegradability of macro pollutants. *Reviews in Environmental Science and Bio/Technology* 3:117- 129. Retrieved: May 29, 2005: http://www.ftns.wau.nl/mt/abai/Angelidaki.pdf.

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

ASTM (1995). Annual book of ASTM standard, 11.04 and 4.08. Philadelphia, P.A.

Ayalan, O., Avnimelech, & Y., Snechter, M. (2000). Alternative MSW management options to reduce global green house emissions- the Israeli examples. *Waste Management and Research*, 18:534-544.

Baere L. (2000). Anaerobic digestion of solid waste: state-of-the-art. *Water Science and Technology*, 41(3):283-90.

Biey E.M., Musibono E.D., & Verstraete W. (2003). Start-up of a multi-stage system for biogas production and solid waste treatment in low-tech countries. *Water Science and Technology*, 48(4):239-243.

Bolzonelia, D., Battistoni, P., Mata-Alvarez, J. & Cecchi, F. (2003). Anaerobic digestion of organic solid wastes: process behavior in transient conditions, *Water Science and Technology*, 48(4):1-8.

Boon, R.D., Chynoweth, D.P., Mah, R.A., Smith, P.H., & Wilkie, A.C. (1993). Ecology and microbiology of biogasification. *Biomass and Bioenergy*, 5:191-202.

Borja, R., Sanchez, E, & Weiland P. (1996). Influence of ammonia concentration on thermophilic anaerobic digestion of cattle manure in up flow anaerobic sludge blanket (UASB) reactors. *Process Biochemistry* 31 (5): 477-483.

Bouallagui H., Haouari, O., Touhami, Y., Cheikh, B.R., Marouani, L. & Hamdia, M. (2004). Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste. *Process Biochemistry* 39:2143-214.

Braber, K. (1995). Anaerobic digestion of municipal solid waste: A modern waste disposal option on the verge of breakthrough, *Biomass and Bioenergy*, 9:365-367.

Brummeler, E.T., Aarnink, M.M.J., & Koster, I.W. (1992). Dry anaerobic digestion of solid waste in a BIOCELL reactor at pilot-plant scale. *Water Science and Technology*, 25(7):301-310.

Callaghana, F.J., Wasea, D.A.J., Thayanithya, K. & Forsterb, C.F. (2002). Continuous co digestion of cattle slurry with fruit and vegetable wastes and chicken manure. *Biomass and Bioenergy* 27:71–77.

Castillo M.E.F., Cristancho, D.E, Victor, A.A. (2005). Study of the operational conditions for anaerobic digestion of urban solid wastes. *Waste Management Online*, Retrieved: February 25, 2005, http:// www.sciencediret.com.

.

Chavez-Vazquez, M., & Bagley, D.M. (2002). Evaluation of the performance of different anaerobic digestion technologies for solid waste. *Csce/Ewri of ASCE Environmental Engineering Conference.*

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

Chynoweth, D.P. (1996). Environmental impact of biomethanogenesis. *Environmental Monitoring and Assessment*, 42:3-18.

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

Chynoweth, D.P. & Pullammanappallil, P. (1996). Microbiology of solid waste. In Palmisano, A.C. & Barlaz, M.A. (Eds.), *Anaerobic digestion of solid waste* (pp71-113*)*. CrC press, Inc, Florida, ISBN: 0-8493-8361-7.

Chynoweth, D.P., Svoronos, S.A., Lyberatos, G., Harmon, J.L., Pullammanappallil, J.L. & Peck, M.J. (1994). Real-time expert system control of Anaerobic Digestion. *Water Science and Technology*, 30(12):21-30.

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

Colleran, E. (1992) Anaerobic digestion of agricultural and food-processing effluents. 199-226. In Fry, J. C., Gadd, G. M., Herbert, R. A., Jones, C. W. & Watson-Craik, I. A. (Eds) *Microbial control of pollution,* Cambridge University Press, Cambridge.

Converti, A., DelBorghi, A., Zilli, M., Arni S. & DelBorghi M.(1999). Anaerobic digestion of the vegetable fraction of municipal refuses: mesophilic versus thermophilic conditions. *Bioprocess Engineering,* 21:371–376.

Das K.C., Smith, M.C., Gattie, D.K. & Boothe, D.D.H. (2002). Stability and quality of municipal solid waste compost from a landfill aerobic bioreduction process. *Advances in Environmental Research,* 6:401-409.

Dayanthi, W.K.C.N. (2003). *Pre-treatment of domestic solid waste by enhanced leaching*. Asian Institute of Technology (AIT), Thailand, Master's thesis no. EV-03-26.

Edelmann, W. & Engeli, H. (1993). Combined digestion and composting of organic industrial and municipal wastes in Switzerland. *Water Science and Technology,* 27(2):169-182.

Edelmann, W., Baier, U. & Ehgeli, H. (2004). Environmental aspects of anaerobic digestion of organic fraction of municipal solid wastes and of agricultural wastes. Retrieved: May, 29, 2005: http://www.arbi.ch/LCA%20AD%20OFMSW.pdf.

Edelmann, W., Schleiss, K. & Joss, A. (2000). Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes, *Water Science and Technology,* 41(3):263-273.

Eriksson, O., Carlsson, R M., Frostell, B., Bjordlund, A., Assefa, G., Sundqvist, J-O. et al. (2005). Municipal solid waste management from system perspective. *Journal of Cleaner Production,* 13:241-253.

Evans, G. (2001). Biowaste and biological waste treatment. James & James (Science Publishers) Ltd. ISBN1-902916-08-5.

Fricke, K., Santen, H. & Wallmann, R. (2005). Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste Management Online,* Retrieved: July 29, 2005, http:// www.sciencediret.com.

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

Ghanem, I.I.I., Guowei G., & Jinfu, Z. (2001). Leachate production and disposal of kitchen food solid waste by dry fermentation for biogas generation. *Renewable Energy,* 23:673-684.

Ghosh, S., Henry, M.P., Sajjad, A., Mensinger, M.C. & Arora, J.L. (2000). Pilot scale gasification of municipal solid wasted by high-rate and two-phase anaerobic digestion. *Water Science and Technology,* 41(3):101-110.

Gunaseelan, V.N. (1997). Anaerobic Digestion of Biomass for Methane Production: A Review. *Biomass and Bioenergy,* 13(1): 83-114.

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

Hanaki, K., Hirunmasuwan, S. & Matsuo, T. (1994). Protection of methanogenic bacteria from low pH and toxic materials by immobilization using polyvinyl alcohol. *Water Research,* 28:877-885.

Hansen, K.H., Angelidaki, I. & Ahring, B.K. (1998). Anaerobic digestion of swine manure: inhibition by ammonia. *Water Research,* 32:5-12.

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

Harmon, J.L., Svoronos, S.A., Lyberatos, G. & Chynoweth, D.P. (1993). Adaptive temperature optimization of continuous anaerobic digesters. *Biomass and Bioenergy,* 4:1-7.

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

Himmelblau, D. (1996). *Basic principles and calculations in chemical engineering,* Second edition. Prentice Hall Inc. New Jersey, ISBN:0133057984.

IEA (International Energy Agency) (2003). Municipal solid waste and its role in sustainability. A position paper prepared by IEA Bioenergy. Retrieved: July 15, 2005 from http:// www.ieabioenergy.com/media/40_IEAPositionPaperMSW.pdf.

Jokela, J.P.Y. & Rintala, J.A. (2003). Anaerobic solubilisation of nitrogen from municipal solid waste *.Re/Views in Environmental Science & Bio/Technology* 2: 67–77.

Jonathan, F.K, Earle, K., Chynoweth, D.P. & Nordstedt, R.A. (1995). Anaerobic Bioconversion: Biogasification of municipal solid waste. Reviewed Bulletin 267, Florida Cooperative extensive service, Institute of food and agricultural science, University of Florida.

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

Kayhanian, K. & Tchobanoglous, G. (1993). Innovative two-stage process for the recovery of energy and compost from the organic fraction o municipal solid waste (MSW). *Water Science and Technology,* 27(2):133-143.

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

Kim, M. & Speece, R.E. (2002a). Reactor configuration-Part I comparative process stability and efficiency of mesophilic anaerobic digestion. *Environmental Technology*, 23:631-642.

Kim, M. & Speece, R.E. (2002b). Reactor configuration-Part II comparative process stability and efficiency of thermophilic anaerobic digestion. *Environmental Technology*, 23:643-654.

Kolsch, F. & Ziehmann, G. (2004). Landfill stability risk and challenges. Retrived on June 15, 2005 from URL: http://www.Jxj.com/wmw/index.html.

Kulkarini, N. (2003). Facts on biofuels in India. Biospectrum .Retrieved on September 6 2005, from http:/www.biospectrumindia.com/content/features/agri/10306105.asp.

Kus, F. & Wiesmann, U. (1995) Degradation kinetics of acetate and propionate by immobilized anaerobic mixed cultures. *Water Research,* 29:1437-1443.

Leikam K. & Stegmann R. (1999). Influence of mechanical-biological pretreatment of municipal solid waste on landfill behavior. *Waste Management and Research,* 17 (8):424-429.

Lester, J.N. & Birkett, J.W. (1999). *Microbiology and Chemistry for Environmental scientists and Engineers.* E & FN Spoon, London. IBBN: 0-41-922680-X.

Lien, N.P.H. (2004). *Dry anaerobic digestion of municipal solid waste as pretreatment prior to landfills.* Asian Institute of Technology (AIT), Thailand, Master's thesis no. EV-04-14.

Lissens, G., Vandevivere, P., De Baere, L., Biey, E.M. & Verstraete, W. (2001). Solid waste digesters: process performance and practice for municipal solid waste digestion. *Water Science and Technology,* 44(8):91-102.

Lopes, W.S., Leite, V. D. & Prasad, S. (2004). Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. *Bioresource Technology*, 94: 261-266.

Ludwig, C., Hellweg, S. & Stucki, S. (2003). *Municipal solid waste management: strategies and technologies for sustainable solutions*. Berlin-Heidelberg-New York, Springer. ISBN: 3-540-44100-X.

Lunning, L., van Zundert, E.H.M. & Brinkmann, A.J.F. (2003). Comparison of dry and wet digestion for solid waste. *Water Science and Technology,* 48(4):15-20.

Mace, S., Bolzonella, D., Cecchi, F. & Mata-Alvarez, J. (2000). Comparison of the biodegradability of the grey fraction of municipal solid waste of Barcelona in mesophilic and thermophilic conditions. *Water science and technology*, 48(4):21-28.

Madigan, M., Martinko, J. & Parker, J. (2003). *Brock biology of microorganisms*. Prentice hall. ISBN: 0-13-049147-0.

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

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

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

Miron, Y., Zeema, G., van Lier, J.B. & Lettinga, G. (2000). The role of sludge retention time in the hydrolysis and acidification of lipids, carbohydrates and proteins during digestion of primary sludge in CSTR system. *Water Resource,* 34(5):1707-1713.

Misi, S.N. & Forster, C.F. (2002). Semi-continuous anaerobic co-digestion of agro-wastes. *Environmental Technology*, 23:445-451.

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

Monnet, F. (2003). An Introduction to Anaerobic Digestion of Organic Wastes. Retrieved: July 29, 2005, http://www.remade.org.uk/Organics/organics_documents.

Mshandetea, A., Bjornssonb, L., Kivaisia, A.K., Rubindamayugia, M.S.T. & Mattiasson, B. Effect of particle size on biogas yield from sisal fibre waste. *Renewable Energy*. Retrieved on December 26, 2005, from www.sciencedirect.com.

Mtz.-Viturtia, A., Mata-Alvarez, J. & Cecchi, F. (1994). Two phase continuous anaerobic digestion of fruit and vegetable wastes. *Resources, Conversation and Recycling,* 13:257-261.

Nopharatana, A., Clarke, W.P., Pullammanappallil, P.C., Silvey, P. & Chynoweth, D.P. (1998). Evaluation of methanogenic activities during anaerobic digestion of municipal solid waste, *Bioresource Technology,* 64 (3):169-174.

Nopharatana, A., Pullammanappallil, P.C. & Clarke, W.P. (2003). A dynamic mathematical model for sequential leach bed anaerobic digestion of organic fraction of municipal solid waste. *Biochemical Engineering Journal*, 13:21-33.

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

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

Oleszkiewicz, J.A. & Poggi-Varaldo, H.M. (1997). High-solids anaerobic digestion of mixed municipal and industrial waste. *Journal of Environmental Engineering,* (ASCE) 123 (11):1087-1092.

Ostrem, K (2004). *Greening waste: anaerobic digestion for treating the organic fraction of municipal solid waste*. Master’s thesis, Columbia University, USA, Retrieved July 15, from, http://www.seas.columbia.edu/wtert /sotos/Osterm_Thesis_final.pdf.

Osterm, K.M., Millrath, K. & Themelis, N.J. (2004). Combining anaerobic digestion and waste-to-energy. *12th North American Waste to Energy Conference (NAWTEC12).*

Pavan, P., Battistoni, P., Cecchi, F. & Mata-Alvarez, J. (2000).Two-phase anaerobic digestion of source sorted OFMSW (organic fraction of municipal solid waste): Performance and kinetic study. *Water Science and Technology*, 41(3):111-118.

Poggi-Varaldo, H.M., Tingley, J. & Oleszkiewicz, J. (1991). Inhibition of growth and acetate uptake by ammonia in batch anaerobic digestion. *Journal of Chemical Technology and Biotechnology*, 52:135-143.

Poggi-Varaldo, H.M. & Oleszkiewicz, J.A. (1992). Anaerobic co-composting of municipal solid waste and waste and sludge at high total solids level. *Environmental Technology,* 13:409-421.

Pokhrel, D. & Viraraghavan, T. (2005). Municipal solid waste management in Nepal: practices and challenges. *Waste Management*, 25(5):555-562.

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

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

Rattananaondom, R. (2005). *Investigation on toxicity and hazardous nature of a municipal solid waste dumpsite*. Asian Institute of Technology (AIT)- Chulabhron Research Institute- Mahidol University, Thailand, Master's thesis no. EV-05-22.

Schieder, D., Schneider, R. & Bischof, F. (2000). Thermal hydrolysis (TDH) as a pretreatment method for the digestion of organic waste. *Water Science and Technology* , 41(3):181-7.

Schink, B. (1997). Energetics of syntrophic cooperation in methanogenic degradation. *Microbiology and Molecular Biology Reviews,* 61:262-280.

Sharma, V.K., Testa, C., Lastella, G., Cornacchia, G. & Comparto, M.P. (2000). Inclined – plug-flow reactor for anaerobic digestion of semi-solid waste. *Applied Energy,* 65:173-185.

Silvey, P., Pullammanappallil, P.C., Blackall, L. & Nichols, P. (2000). Microbial ecology of the leach bed anaerobic digestion of unsorted municipal solid waste. *Water Science and Technology,* 41(3):9-16.

Six, W. & Baere, L.D. (1992). Dry anaerobic conversion of municipal solid waste by means of the Dranco process. *Water Science and Technology*, 25(7):295-300.

Stegmann R. (2005). Mechanical biological pretreatment of municipal solid waste. In *Proceedings of Tenth International Waste Management and Landfill Symposium,* Cagliari, Italy. Enviromental Sanitary Engineering Centre.

Sung, S. & Liu, T. (2003). Ammonia inhibition on thermophilic anaerobic digestion. *Chemosphere,* 53:43-52.

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

Teixeira, A.A., Chynoweth, D.P., Owens, J.M., Rich, E.R., Dedrick, A.L. & Haley, P.J. (2004). Prototype space mission SEBAC biological solid waste management system. *In Proceedings of 34th International conference on environmental systems (ICES),* Paper 2004-ICES-098.

Tränkler J., Visvanathan, C. & Kuruparan, P. (2004). Mechanical Biological Waste Treatment In South-East Asia - Process Features And Treated Waste Performance, In *Proceedings APLAS, 3rd Asia Pacific Landfill Symposium,* (pp.191-198*)* Kitakyushu, Japan.

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

Vaidya, D.R. (2002). *Solid Waste Degradation, Compaction and Water Holding Capacity* Virginia Polytechnic Institute and State University, USA. Master's thesis.

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

Veeken, A., Kalyuzhnyi, S., Scharff, H. & Hamelers, B. (2000). Effect of pH and VFA on hydrolysis of organic solid waste. *Journal of Environmental Engineering* December:1076-1081.

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

Verma, S. (2002). *Anaerobic digestion of biodegradable organics in municipal solid wastes*. Master's thesis, http://www.seas.columbia.edu/earth/vermathesis.pdf.

Vieitez E.R., Mosquera J. & Ghosh S. (2000). Kinetics of accelerated solid-state fermentation of organic-rich municipal solid waste. *Water Science and Technology,* 41(3):231-238.

Vieitez, E.R. & Ghosh, S. (1999). Biogasification of solid wastes by two-phase anaerobic fermentation**.** *Biomass and Bioenergy***,** 16(5):299-309**.**

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

Visvanathan C. (2004). Mechanical biological pre-treatement of solid waste prior to landfill. Retrived February 2006, http://www.seauema.ait.ac.th/download /conference /presentation /keynote/KeynoteVisu.pdf.

Wang, J.Y., Xu, H-L., Zhang, H. & Tay, J-H. (2003). Semi-continuous anaerobic digestion of food waste using a hybrid anaerobic solid-liquid bioreactor. *Water Science and Technology*, 48(4):169-174.

WPCF (1987). Anaerobic sludge digestion. Manual of Practice No.19. Second edition. Water pollution control federation. Alexandria, VA.

Zhang, B., Zhang, S.C., Shi, H.Z. & Cai, W.M. (2005). Effect of pH on hydrolysis and acidogenesis of Kitchen waste in two phase anaerobic digestion. *Environmental Technology*, 26: 329-339.

Zupancic, G.D. & Ros, M. (2003). Heat and energy requirements in thermophilic anaerobic sludge digestion, *Renewable Energy*, 28:2255-2267.

.

Appendix A: Photographs

Unsorted Waste

Sorted Waste

Shredding

Reactor Feeding

Exp. on progress

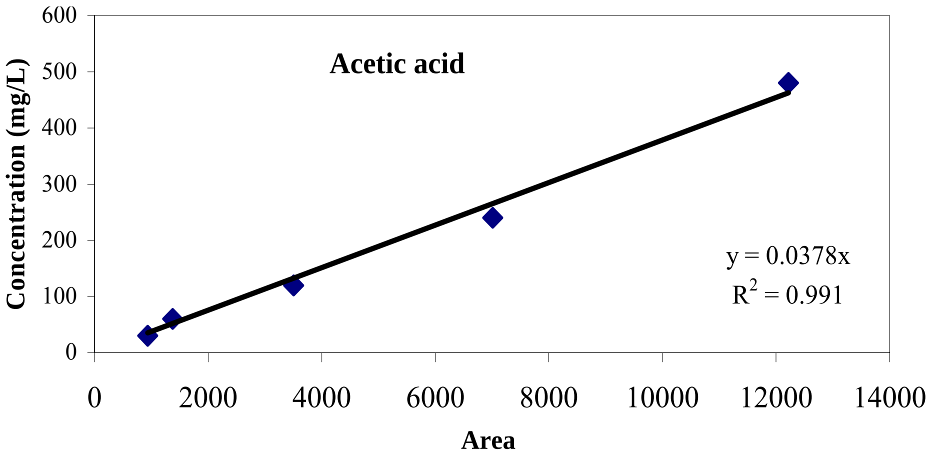
BMP Assay

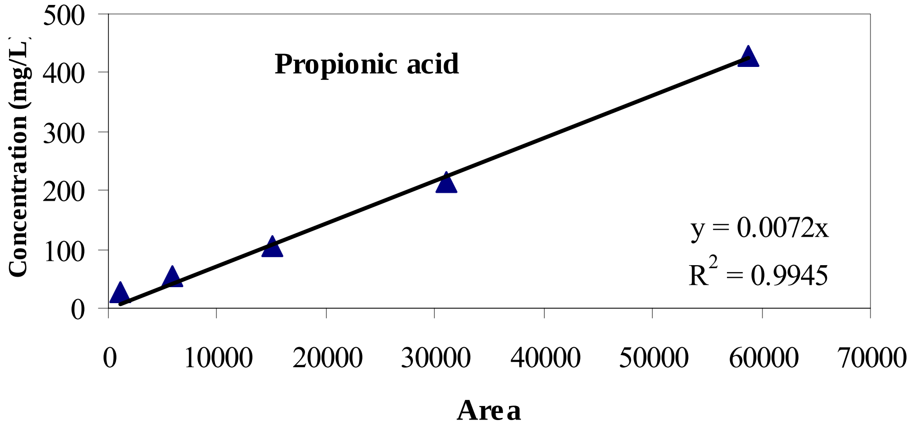
Biogas Analysis

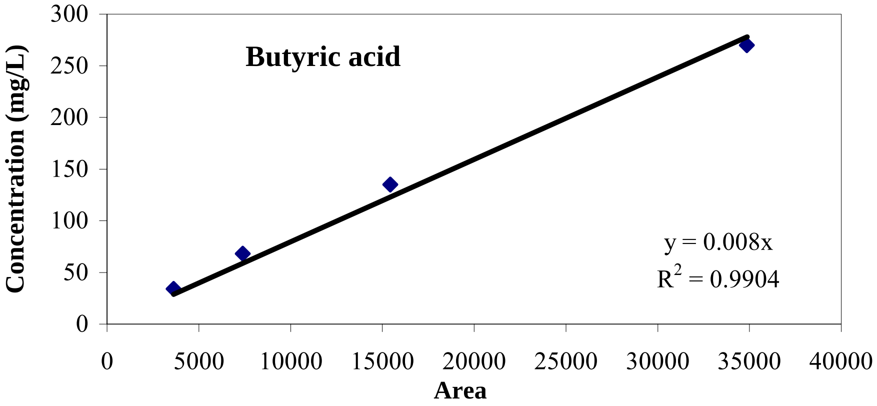
Digestate

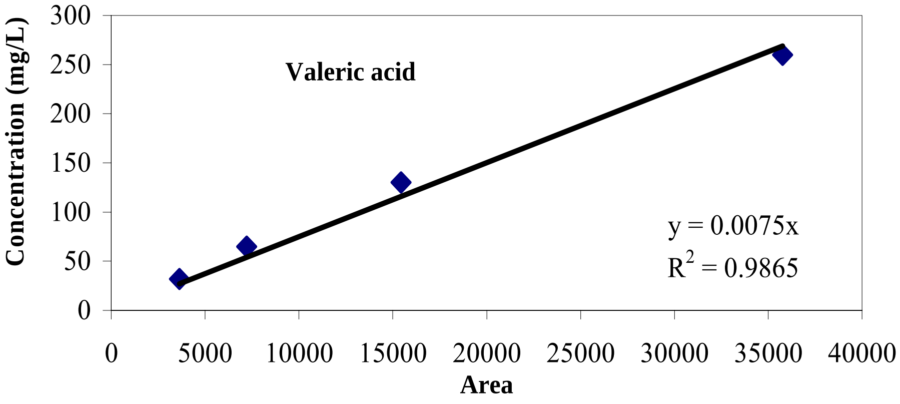
Sandbed

Appendix- B-1: Family of VFA Standard Curves

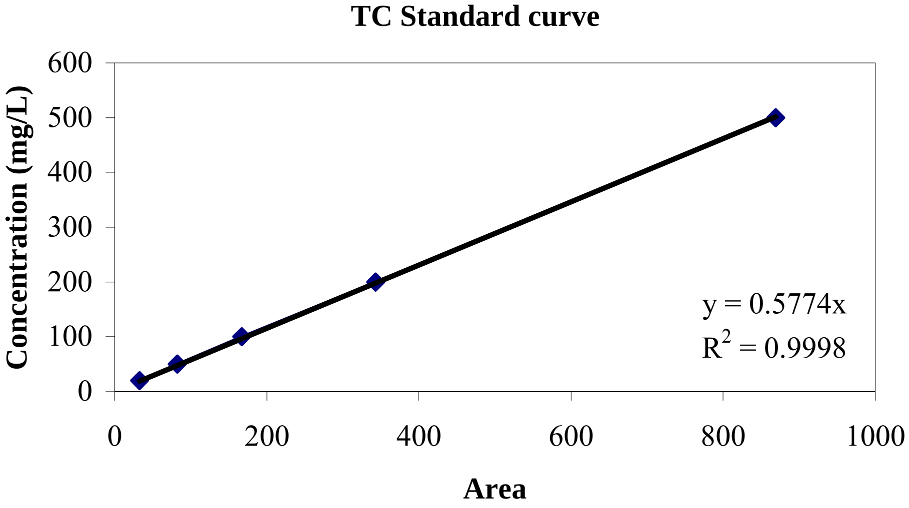


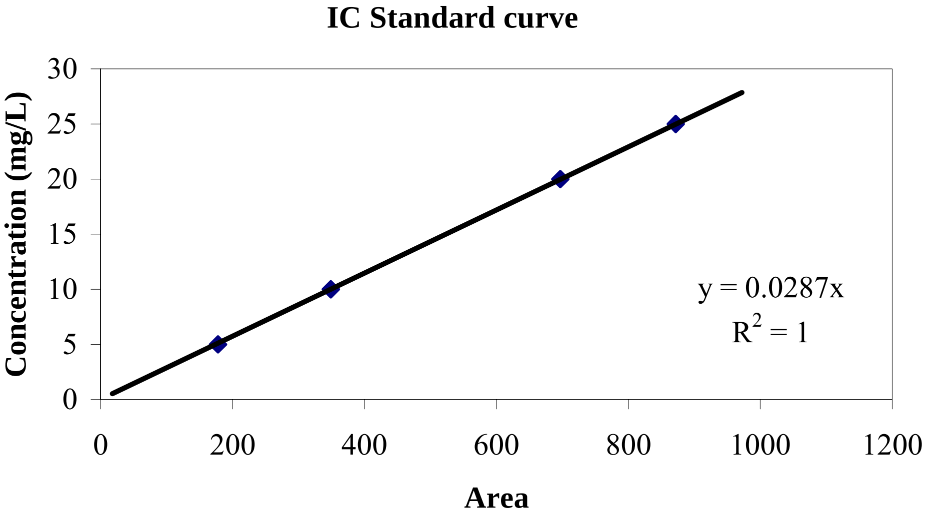






Appendix- B-2: TC and IC standard Curves





Appendix B-3: Sample Calculations

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

Weight of sample before drying =1000 g
Weight of sample after drying = 194 g

$$\% \text{ MC} = \frac{1000g - 194g}{1000g} \text{ x } 100 = 80.6\ \%$$

% TS = 100 – 80.6 = 19.4%

Weight of sample after 105°C = 1.79 g

Weight of sample after 550°C = 0.528 g

$$\% \text{ VS} = \frac{1.79g - 0.528g}{1.79g} \text{x}100 = 70.5\%$$

Total WW of sample = 200kg

Dry weight = $(WW \times \%TS)$ = $200kg \times 0.194 = 38.8$ kg

Volatile weight = $(Dryweight \times \%VS)$= $38.8kg \times 0.705 = 27.4$ kg

2. Calculation of DOC load (pilot scale Run 2, reactor 1)

DOC load Day 1

DOC concentration C = 6503 mg/L **Table C-2**
Leachate removal V = 185 L
Dry weight of sample TS = 19.4 kg

$$\frac{C \times V}{TS} = \frac{7603 \times 185}{19.45(1000)} = 63.27g \text{ DOC/kgTS}$$

DOC load Day 2

DOC concentration C = 6819 mg/L
Leachate removal V = 180 L

$$\frac{C \times V}{TS} = \frac{6819 \times 180}{19.45(1000)} = 63.27g \text{ DOC/kgTS}$$

DOC load Day 3

DOC concentration C = 5985 mg/L
Leachate removal V = 185 L

$$\frac{C \times V}{TS} = \frac{5958 \times 185}{19.45(1000)}5 = 56.82g \text{ DOC/kgTS}$$

DOC cumulative load = $\sum \text{DOC load} = 182.1g$

3. **Calculation of methane production 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 chromatogram) * K
K = constant = $1.7759*10^{-10}$

Area$_{25}$ (before removal) =669120 (25: Run time in days)
Mass of CH_4 in sample = $669120*1.7759*10^{-10}$ = 118.83µg

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

Volume of headspace in reactor V= 2205 mL

Mass of CH_4 in reactor:

$$M_{25} \text{ (reactor, before removal)} = \frac{V}{0.2} * m \text{ (sample)}_{25} = \frac{2205}{0.2} * 118.83\mu g$$
$$= 1.31 \text{ (g)}$$

$$M_{25.} \text{ (reactor, after removal)} = \frac{V}{0.2} * m \text{ (sample)}_{72.0}$$
$$= \frac{2205}{0.2} * 46.04 \ \mu g$$
$$= 0.508 \text{ (g)}$$

Step 3: Determination of amount removal

m_i (removal) = m_i (before removal) – m_i (after removal)
m_{25} (removal) = 1.31- 0.508 = 0.802 (g)

Step 4: Determination of cumulative gas production (g)
Cumulative mass production= 1.26 + (0.508 + 0.802)= 2.57 (g)
$m_{cumulative}$ = Cumulative mass production – mass removed = 2.57 - (0.802)
$m_{cumulative}$ = 1.76 (g)

Step 5: Determination of cumulative gas production (L in SATP)

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

P: standard pressure (1 atm)
V: CH_4 production in volume (L in SATP)
m: CH_4 production in mass (g)
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)

$$V_{25} = \frac{m}{MP} * RT = \frac{1.76}{16(1)}\left(8.205 \times 10^{-2}\right)298 = 2695 \text{ (NmL)}$$

4. Calculation of methane potential

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

5. Energy balance

a) SEBAC process

Operation:

1. Pre-treatment: Waste shredding

2 .Heating requirement: Thermophilic condition

3. Leachate pumping: Coupled and uncoupled reactors

4. Final stage: to end the process: Aeration: 5 L/min (6 hours)

1. Energy used (Cycle I: 26 days of operation)

a) Waste shredding

0.7 L of gasoline was consumed by the cutting machine to shred 200 kg of waste (as observed) to the size of 30mm.

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
116, 324.8 KJ/gal (1gal/3.785L) (0.7 L) = 21, 513.2 KJ/reactor

b) Heating requirements

The anaerobic reactions are exothermic and can keep heated itself with lesser energy input. The energy consumed for heating water from 29 °C to 55 °C.

Basis: Entire heating operation
$H = m . \rho . \Delta T$--(Himmelblau, 1996)
$H = 95 \times 10^3$ g (1 cal/g °C) (55°C - 29°C)
H = 2470 Kcal
H = 2470 Kcal (4.18 KJ/Kcal) = 10324.6 KJ

c) Leachate circulation (pumping)

Power required by the pump is:
Power (KW) = (Q x D x H) / 6, 130.25

Where, Q = pump capacity (L/min); 3L/min
D = density of water (kg/L); 0.9933316 kg/L at 37°C
H = total head (m); 1.9 m

6, 130.25 = conversion factor

$KW_{(pump)}$ = (3 x 0.9933316 x 1.9)/ 6,130.25
$KW_{(pump)}$ = 0.00092 KW = 0.92 W = 0.92 J/sec

Since circulation was done for 30 minutes everyday,
Power used by pump each day = 1656 J/day

Pump $_{(R1)}$, Operates for 7 days: Pump $_{(R2)}$ = Operates for 23 days:
So for 23 days in Fresh waste reactor and 7 days in old reactor, = (23+7) = 30 days
1656 * 30 = 49680 J =49.68 KJ

d) Aeration (final stage)

Power required by the air compressor pump is:
Power (KW) = (QxDxH) / 6,130.25

Where, Q = pump capacity (L/min); 200L/min
D = density of air (kg/L); 0.001165 kg/L at 30°C
H = total pressure head (m); (75 psi – 20 psi) = *55 psi*
6,130.25 = conversion factor

55 psi = 38, 668.8 kg/m^2
Pressure head = (38, 668.8 kg/m^2*)/ (1.165kg/m*^{3}*) = 33, 192 m*

$KW_{(\text{air compressor})}$ = (200 x 0.001165 x 33, 192)/ 6,130.25
$KW_{(\text{air compressor})}$ = 1.3 KW

P_1 = 75 psig + 14.7 = 89.7 psia (1 atm/14.7 psia) = 6.1 atm
P_2 = 20 psig + 14.7 = 34.7 psia (1 atm/14.7 psia) = 2.36 atm

Amount of air when the inside pressure of tank is 75 psig:
$N_1 = P_1 V_1 / R T$
= (6.1 atm x 92 L)/ (0.08205 x 303)
= 22.57 moles

Amount of air when the inside pressure of tank is 20 psi:
$N_2 = P_2 V_2 / R T$
= (2.36 atm x 92 L)/ (0.08205 x 303)
= 8.7 moles

Amount of air release
N = 22.57 – 8.7 = 13.87 moles
Mass = 13.87 moles/ (29 g/mole)
= 402.23 g or 0.4 kg

Volume = 0.4 kg (1L/0.001165 kg)
= 345 L

Time required finishing the stored compressed air (from 75 psig to 20 psig):

Time = 345 L (1min/L) = 345 min = 5.7 hours or approximately 6 hours

1.3 KW of power is needed to supply the air for 1 reactor for 6 hours. The air compressor pump works for 1.7 min.

345 L/ 200 L = 1.7 min.

Basis: Working duration of air compressor for 6 hr of operation
6 hr/ 1.15 hr = 5.2 times
1.7 min (5.2) = 8.84 min
8.84 min (60 sec/min) (1.3 KJ/sec) = 689.52 KJ

E (used) = E (pretreatment) + E (heating) + E (pumping) + E (final stage: aeration)
E (used) = 21, 513.2 + 10324.6 KJ+ 49.68 KJ+689.52 KJ
=32577.31 KJ

2. Energy produced from the process.

As calorific value to the biogas depends upon the methane content, total volume of biogas only above 50% methane content has been computed in the energy calculation. The average methane content biogas was 60 %.

Calorific value of biogas = 5000 Kcal/m^3 ----------------------------- (Kulkarni, 2003)

Total volume of the gas produced= 5927.2 L
Volume of gas produced below 50 % methane = 1277.3 L (**Table C-11**)
Total volume of gas with net calorific value =5927.2-1277.3= 4649.9 L=4.65 m^3
= 4.65 m^3 (5000Kcal/m^3) = 23250 Kcal
23250 Kcal (4.18KJ/Kcal) = 97185 KJ = 97.2 MJ=5.31MJ /kgVS

3. Net energy gain

E (gained) = E (produced) – E (used)
E (gained) = 97185 – 32577 KJ
E (gained) = 64608 KJ =64.6 MJ
E (gained) = 3.58 MJ/kg VS

Cycle II

1. **Energy used (Cycle II: 23 days of operation)**

a) Power used for Waste shredding = 21, 513.2 KJ

b) Heating requirements=10324.6 KJ

c) Power required in pumping =

Power (KW) = (Q x D x H) / 6, 130.25

Where, Q = pump capacity (L/min); 3L/min
D = density of water (kg/L); 0.9933316 kg/L at 37°C
H = total head (m); 1.9 m
6, 130.25 = conversion factor

$KW_{(pump)}$ = (4 x 0.9933316 x 1.9)/ 6,130.25
$KW_{(pump)}$ = 0.000123 KW = 1.23 W = 1.23 J/sec

Since circulation was done for 30 minutes everyday,
Power used by pump = 1.23 *1800 =2214 J/day

Pump $_{(R1)}$, Operates for 7 days: Pump $_{(R2)}$ = Operates for 21 days:
So for 21 days in Fresh waste reactor and 7 days in old reactor, = (21+7) = 28 days
2214 * 28 = 61992 J =61.99 KJ

d) Aeration (final stage) =689.52 KJ

E (used) = E (pretreatment) + E (heating) + E (pumping) + E (final stage: aeration)
E (used) = 21, 513.2 + 10324.6 KJ+ 61.99 KJ+689.52 KJ
=32589.31KJ

E (used) = 32.58 MJ=1.9MJ/kg VS

2. Energy produced from the process

Total volume of the gas produced= 6795.7 L
Volume of gas produced below 50 % methane = 1835.4 L (**Table C-12**)
Total volume of gas with net calorific value =6795.7 -1835.4 = 4660.3 L= 4.66 m^3
= 4.66 m^3 (5000Kcal/m^3) = 23300 Kcal
23300 Kcal (4.18KJ/Kcal) = 97394 KJ = 97.39 MJ=5.78MJ /kg VS

3. Net energy gain

E (gained) = E (produced) – E (used)
E (gained) = 97394 – 32589 KJ
E (gained) = 64805 KJ = 64.8 MJ
E (gained) = 3.85 MJ/kg VS

Cycle III

1. Energy used (Cycle III: 21 days of operation)

a) Power used for Waste shredding = 21, 513.2 KJ

b) Heating requirements=10324.6 KJ
c) Power required in pumping =61992 J =61.99 KJ

d) Aeration (final stage) =689.52 KJ

E (used) = E (pretreatment) + E (heating) + E (pumping) + E (final stage: aeration)
E (used) = 21, 513.2 KJ+ 10324.6 KJ+ 61.99 KJ+689.52 KJ
=32589.31KJ

E (used) = 32.58 MJ=1.76MJ/kg VS

2. Energy produced from the process

Total volume of the gas produced= 7762.77 L
Volume of gas produced below 50 % methane = 2249.7 L (**Table C-13**)
Total volume of gas with net calorific value =7762.7 -2249.7 = 5513.07 L= 5.55 m^3
= 5.55 m^3 (5000Kcal/m^3) = 27750 Kcal
27750 Kcal (4.18KJ/Kcal) = 115995 KJ = 115.995 MJ=6.27 MJ /kg VS

3. Net energy gain

E (gained) = E (produced) – E (used)
E (gained) = 115995– 32589 KJ
E (gained) = 83406 KJ = 83.40 MJ
E (gained) = 4.5 MJ/kg VS

b) Continuous digestion

1. Energy used

a) Waste shredding

0.4 L of gasoline was consumed by the cutting machine to shred 100 kg of feedstock to 10 mm sized particle (as observed),

Energy used to shred 794 kg of waste =794*0.004L/kg=3.176~3.2 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
116, 324.8 KJ/gal (1gal/3.785L) (3.2 L)
98345.93395 KJ=98.345 MJ

b) Heating requirements

Basis: Entire heating operation
H = m. ρ. Δ T--(Himmelblau, 1996)

Total amount of water heated is estimated to be 129L (during 134 days of operation),
H = 129 X10^3 g (1 cal/g °C) (55°C - 29°C)
H = 5694 Kcal (4.18 KJ/Kcal) = 23800.92 KJ=23.8 MJ

E (used) = E (pretreatment) + E (heating)
=23.8+98.34 =122.14 MJ

2. Energy produced

Total volume gas produced with methane content >50%=23.8 m^3 **(Table D-2)**
Calorific value of the gas= 5000*23.8 =115823 Kcal =484140.1KJ
= 484.14 MJ

3. Net Energy gained

E (gained) = E (produced) – E (used)
= (484.14-122.14) MJ
= 361.85 MJ
= 5.4 MJ/kg VS

6. Example of Mass balance for 10 kg feed input

Characteristics of Input Feedstock

Total feedstock wet weight = 10 kg
Moisture content = 100 -12 = 88%
Total moisture in a given weight of waste = $0.88 \times 10 = 8.8kg$
Total dry solid present in the waste (TS) = $(1-0.88) \times 10 = 1.2kg$

Characteristics Withdrawn Feedstock

Total Solid in Leachate = 25 g/L
Moisture content of digestate = 90%
Total digestate to be withdrawn (kg) = Y
Total leachate to be withdrawn (L) = L

Water Mass Balance

Total liquid intake = Total liquid out

$$8.8 = (0.9Y) + L \text{ -------------------Eq. (1)}$$

Solid Mass Balance

Total solid loss in leachate = $\frac{25}{1000}L$

With daily biogas production of 250 L (50% CH_4 and 50% CO_2), Total solid loss in biogas production (kg) is calculated using:

$$\{250 \times [16 \times (50/100) + 44 \times (50/100)]/22.413\} = 0.3346\text{kg}$$

Dry solid intake = Dry solid out

1.2 = (25/1000)*L + (0.1)Y+0.336 ----------------- Eq. (2)

Solving Eqs (1) and (2) we get: $\begin{cases} y = 6.6\ \text{kg} \\ L = 2.9\ \text{Litres} \end{cases}$

Appendix C: Pilot scale SEBAC

Table C-1: Biogas production

Date	Run time (Days)	Gas production rate (L/day)	Temperature °C	Ambient pressure (*mb*)	Vapour pressure (*mb*)	Dry volume of gas produced (L/day)	Cumulative volume of gas produced[1] (L)	Gas composition		Cumulative[1] CH_4 production (L)
								CO_2 (%)	*CH_4 (%)	
10-Sep	8	50.0	29.0	1018.0	32.4	51.64	51.64	82.5	17.5	9.04
11-Sep	9	59.0	29.3	1016.0	33.1	60.99	112.63			
12-Sep	10	59.0	27.9	1016.0	31.8	60.91	173.54	81.5	18.5	31.40
13-Sep	11	51.0	28.8	1016.0	33.8	52.76	226.29			
14-Sep	12	53.0	28.8	1011.0	29.0	54.57	280.86	76.3	23.7	56.15
15-Sep	13	44.0	28.9	1016.0	40.6	45.83	326.69	76.3	23.7	67.02
16-Sep	14	51.0	28.9	1016.0	40.6	53.12	379.81	76.2	23.8	79.66
17-Sep	15	35.0	28.9	1017.0	32.7	36.16	415.97	76.2	23..8	88.16
18-Sep	16	35.0	29.3	1016.5	32.2	36.14	452.12	73.7	27.3	98.03
19-Sep	17	52.0	28.0	1014.5	35.2	53.87	505.99	71.7	28..3	113.27
20-Sep	18	51.0	30.4	1014.5	30.5	52.58	558.57	66.5	33.5	130.88
21-Sep	19	37.0	30.0	1019.0	28.4	38.06	596.63	62.9	37.1	145.01
22-Sep	20	37.8	30.5	1018.5	27.8	38.86	635.49	62.8	37.2	159.46
23-Sep	21	38.5	30.6	1018.3	28.7	39.62	675.11	62.8	37.2	174.20
24-Sep	22	34.4	30.8	1014.5	33.9	35.59	710.70	62.6	37.4	187.51
25-Sep	23	38.2	30.2	1017.5	30.3	39.37	750.07	62.0	38.0	202.47
26-Sep	24	34.3	30.5	1017.0	33.3	35.46	785.53	62.0	38.0	215.95
27-Sep	25	36.4	31.6	1014.0	31.7	37.57	823.10	61.9	38.1	230.26
28-Sep	26	40.5	31.3	1015.0	31.2	41.78	864.89	60.2	39.8	246.89
29-Sep	27	35.2	29.9	1017.0	27.9	36.19	901.08	59.9	40.1	261.41
30-Sep	28	20.3	28.9	1019.0	30.0	20.92	922.00	59.7	40.3	269.83
1-Oct	29	25.3	31.5	1019.5	33.8	26.17	948.17	59.6	40.4	280.41

2-Oct	30	22.2	31.1	1018.5	36.0	23.01	971.18	57.4	42.6	290.21
3-Oct	31	35.0	30.8	1016.5	28.8	36.02	1007.20	56.8	43.2	305.77
4-Oct	32	24.9	30.9	1016.5	33.1	25.74	1032.94	55.3	44.7	317.28
5-Oct	33	25.9	29.3	1017.5	31.0	26.71	1059.65	54.8	45.2	329.36
6-Oct	34	15.7	29.9	1018.5	29.8	16.17	1075.82	53.2	46.8	336.93
7-Oct	35	38.0	30.3	1017.5	30.5	39.17	1115.00	51.8	48.2	355.81
8-Oct	36	35.2	30.0	1017.0	29.4	36.25	1151.25	49.9	50.1	373.97
9-Oct	37	35.3	28.8	1017.5	32.2	36.45	1187.70	47.6	52.4	393.07
10-Oct	38	32.0	30.0	1018.3	27.7	32.89	1220.59	47.6	52.4	410.31
11-Oct	39	35.1	30.7	1017.5	28.5	36.11	1256.71	47.5	52.5	429.25
12-Oct	**40**	**35.0**	**29.8**	**1018.0**	**31.6**	**36.12**	**1292.83**	**47.2**	**52.8**	**448.32**
13-Oct	41	39.0	30.5	1017.5	30.6	40.21	1333.04	47.1	52.9	469.59
14-Oct	42	50.6	29.5	1018.5	31.3	52.20	1385.24	46.9	53.1	497.31
15-Oct	43	49.8	30.5	1018.5	31.6	51.39	1436.64	45.7	54.3	525.22
16-Oct	44	68.0	29.3	1019.5	31.7	70.18	1506.82	45.43	54.57	563.52
17-Oct	45	98.3	29.5	1020.5	30.3	101.31	1608.13	44.8	55.2	619.44
18-Oct	46	134.6	29.8	1021.0	31.3	138.86	1746.98	43.8	56.2	697.48
19-Oct	47	119.3	29.9	1019.5	29.1	122.81	1869.79	43.4	56.6	766.98
20-Oct	**48**	**101.6**	**29.6**	**1019.0**	**27.1**	**104.38**	**1974.16**	**43.0**	**57.0**	**826.48**
21-Oct	49	142.0	29.5	1019.0	27.1	145.88	2120.04	41.2	58.8	912.26
22-Oct	50	157.0	29.5	1019.5	25.3	161.00	2281.04	40.9	59.1	1007.40
23-Oct	51	148.2	28.5	1019.5	29.1	152.55	2433.59	40.7	59.3	1097.87
24-Oct	52	167.1	27.9	1021.0	29.5	172.07	2605.66	40.3	59.7	1200.60
25-Oct	53	217.4	28.3	1020.0	29.0	223.76	2829.43	40.2	59.8	1334.41
26-Oct	54	245.4	30.0	1019.5	29.9	252.81	3082.24	39.8	60.2	1486.60
27-Oct	55	274.4	28.7	1019.0	31.7	283.21	3365.45	39.7	60.3	1657.38

28-Oct	56	287.2	30.4	1021.5	28.9	295.56	3661.01	41.8	58.2	1829.39
29-Oct	57	295.2	29.8	1029.0	29.4	303.88	3964.90	41.1	58.9	2008.38
30-Oct	58	338.8	29.5	1018.0	32.3	349.90	4314.80	40.5	59.5	2216.57
31-Oct	59	417.4	29.1	1019.0	27.1	428.80	4743.60	41.2	58.8	2468.71
1-Nov	60	347.2	27.9	1018.5	27.7	356.91	5100.51	40.3	59.7	2681.78
2-Nov	61	389.0	30.1	1018.0	25.8	399.12	5499.62	39.8	60.2	2922.05
3-Nov	62	289.9	30.8	1017.5	29.0	298.40	5798.03	39.7	60.3	3101.99
4-Nov	63	250.0	30.4	1018.0	28.3	257.15	6055.18	40.4	59.6	3255.25
5-Nov	64	201.4	28.5	1019.5	29.6	207.42	6262.60	39.8	60.2	3380.12
6-Nov	65	137.4	29.3	1019.5	33.1	142.01	6404.61	40.10	59.9	3465.18
7-Nov	66	89.7	30.0	1018.5	31.3	92.54	6497.15	40.17	59.83	3520.55
8-Nov	67	88	29.9	1020.5	29.2	90.59	6587.75	40.24	59.76	3574.69
9-Nov	68	93.5	28.8	1021.0	29.5	96.28	6684.03	40.31	59.69	3632.16
10-Nov	69	50.4	29.8	1019.0	31.6	52.01	6736.04	40.38	59.62	3663.17
11-Nov	70	84.5	30.0	1017.0	35.4	87.55	6823.59	40.45	59.55	3715.30
12-Nov	71	75.6	29.3	1018.0	35.2	78.31	6901.90	40.52	59.48	3761.88
13-Nov	72	56.3	29.5	1018.5	31.4	58.09	6959.99	40.3	59.7	3796.56
14-Nov	73	65.5	30.1	1018.0	35.1	67.84	7027.83	39.8	60.2	3837.40
15-Nov	74	82.4	30.0	1016.0	30.4	84.94	7112.77	39.8	60.2	3888.53
16-Nov	75	66.6	30.0	1017.5	30.6	68.67	7181.43	40.1	59.9	3929.66
17-Nov	76	43.2	29.8	1018.0	30.5	44.53	7225.97	39.7	60.3	3956.52

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

* [CH_4/ (CH_4+CO_2)]

Table C-2: Leachate characteristics during flushing Run 1

Description	Run (days)				Pollutant Load (g/kg.TS)			
	0	1	2	3	1	2	3	Cumulative load
Leachate Generated (L)	180	185	180	185				
TCOD (mg/L)		8304	9640	6936	79.19	89.44	66.14	234.77
SCOD (mg/L)		6832	8248	5686	65.15	76.53	54.22	195.90
NH_4-N		580	885	530	5.53	8.21	5.05	18.80
TKN (mg/L)		873	1220	803	8.33	11.32	7.66	27.30
TDS		7360	5160	4520	70.19	47.88	43.10	161.16
Alkalinity		2500	1800	2200	23.84	16.70	20.98	61.52
VFA		5267	5523	4826	50.23	51.24	46.02	147.49
DOC		6503	6819	5958	62.01	63.27	56.82	182.10

Table C-3: Mature leachate characteristics Run 1

Run time	pH	Alkalinity	DOC	VFA	NH_4-Nitrogen
(days)		mg/L	mg/L	mg/L	mg/L
40	7.07	4400	4600	2228	770
41	7.21	4300	4300	2256	815
42	7.34	4500	4400	2152	850
43	7.31	4800	4100	2340	872
44	7.43	5100	4180	2188	874
45	7.41	5300		2240	883
46	7.45	5400	4200		918
47	7.46	5600	4100	2196	936
48	7.51	5800	3520	1835	927
49	7.69	5800			928
50	7.71	6200	3650	1666	934
51	7.82	6500	3540	2340	932
52	7.83	6700	3590	2093	935
53	7.88	7000	3420	2019	850
54	7.89	7100	3530	1689	
55	7.84	7100	3400	1452	
56	7.84	7100	3300	1499	
57	7.86	7200	2380		
58	7.83	7200			
59	7.84	7300	2360		
60	7.81	7100	2470		
61	7.83	6900	2360		

Table C-4: Leachate characteristic Stabilized reactor SEBAC cycle I

Run time (days)	pH	ORP	Alkalinity mg/L	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
1	7.89	-375.7	7500	2080	2114	1060
2	7.83	-386.9	7000	5160	2955	966
3	7.89	-388.5	7600	5880	1862	980
4	7.46	-387.6	7800	3970	1655	1050
5	7.83	-386.9	7700	4440	1857	1090
6	7.98	-402.1	7800	3900	1930	1060
7	7.87	-399.6	7900	2820	1731	966

Table C-5: Leachate characteristic of Fresh reactor SEBAC cycle I

Run time (days)	pH	ORP (mV)	Alkalinity (mg/L)	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
1	5.70	-93.2	5400	7200	4143	784
2	6.48	-96.8	7800	7060	4553	756
3	6.81	-224.6	8300	6020	3802	784
4	6.89	-289.5	8600	6480	2962	784
5	6.99	-300.4	8300	5460	3317	784
6	7.04	-315.6	8700	4340	2849	1190
7	7.22	-384.5	9200	3900	2815	1218
8	7.45	-386.6	9300	4480	2739	1288
9	7.47	-399.4	9300	3040	2555	1274
10	7.70	-401.2	9400	4210	2305	1260
11	7.88	-402.6	9100	3640	2111	1274
12	7.98	-399.5	9400	3350	2347	1218
13	7.89	-398.9	9000	3420	1458	1260
14	7.98	-397.9	9100	3130	1408	1190
15	7.87	-397.8	9400	3080	1112	1232
16	7.98	-402.8	8900	3370	1160	1167
17	8.01	-403.4	9300	3100	1275	1204
18	8.01	-401.8	8800	2540	890	1162
19	7.98	-398.6	8900	2620	869	1204
20	7.99	-399.0	9000	2630	727	1190
21	8.02	-398.5	9200	2130	601	1176
22	7.89	-400.2	9000	1920	557	1162
23	7.99	-398.4	9100	1710	466	1204
24	7.91	-386.9	9300	1700	434	1232
25	7.98	-393.6	8900	1690	422	1218

Table C-6: Leachate characteristics Stabilized reactor SEBAC cycle II

Run time (days)	pH	Alkalinity (mg/L)	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
0	8.01	8100	1400	570	1218
1	7.85	8000	4320	2261	1260
2	7.34	7600	5620	3105	1190
3	7.42	7800	5890	3523	1232
4	7.65	8000	4960	3304	1167
5	7.76	8200	4060	2301	1204
6	7.89	8400	4140	2404	1162
7	7.88	8300	4030	2160	1204

Table C-7: Leachate characteristic Fresh reactor SEBAC cycle II

Run time (days)	pH	Alkalinity (mg/L)	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
0	5.46	3900	6010	3017	486
1	6.29	4100	6040	3829	784
2	6.43	4300	6280	4601	1190
3	6.69	5200	6480	4046	1218
4	6.87	5500	6260	3999	1260
5	7.05	5800	6110	3820	1274
6	7.26	6300	5960	3592	1218
7	7.48	6900	5840	3389	1260
8	7.50	7100	5640	3423	1190
9	7.64	7300	5170	3043	1302
10	7.81	7600	4820	2965	1316
11	7.93	7700	4640	2602	1344
12	7.86	7600	4180	2571	1330
13	7.99	8400	4080	2118	1358
14	7.98	9000	3870	1900	1400
15	7.89	8900	3600	1876	1386
16	8.08	8900	3570	1765	1372
17	7.99	9100	3360	1530	1218
18	7.98	9000	3080	1000	1260
19	7.88	9200	3100	945	1342
20	7.97	9100	2140	875	1356
21	8.04	9400	1780	721	1274
22	7.99	9300	1550	660	1288
23	8.01	9200	1200	560	1342

Table C-8: Leachate characteristic Fresh reactor SEBAC cycle III

Run time (days)	pH	Alkalinity (mg/L)	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
0	8.01	8800	1200	566	1232
1	7.82	8500	4710	2010	1260
2	7.42	8200	6760	3830	1204
3	7.62	8300	6000	3460	1232
4	7.71	8200	5710	3589	1218
5	7.75	8400	5140	3226	1204

Table C-9: Leachate characteristic Fresh reactor SEBAC cycle III

Run time (days)	pH	Alkalinity (mg/L)	DOC (mg/L)	VFA (mg/L)	NH_4-Nitrogen (mg/L)
0	5.87	4400	7060	4730	1162
1	6.48	4700	7200	5104	1176
2	6.86	5400	7466	5416	1190
3	7.05	6800	7370	4377	1204
4	7.25	7400	6830	3844	1232
5	7.43	7800	6120	3675	1218
6	7.58	8100	5890	3623	1232
7	7.62	8300	5320	3509	1356
8	7.79	8200	5180	3222	1380
9	7.89	8100	5160	2267	1368
10	8.01	8100	5020	2325	1392
11	7.99	8300	4450	1735	1342
12	7.98	8300	4360	1595	1392
13	7.99	8500	3940	1689	1380
14	8.00	8600	3140	1154	1368
15	8.08	8700	3090	1097	1368
16	7.98	8800	2960	956	1368
17	7.99	8800	2780	833	1392
18	7.96	9000	2120	615	1380
19	7.98	8900	1750	560	1356
20	8.01	9000	1590	644	1344
21	8.04	9100	1290	566	1356

Table C-10: Biogas production in Stabilized reactor SEBAC cycle I

Run time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar(*mb*)	Vapour Pressure Mllibar(*mb*)	Dry volume of gas (L/day)	Volume of gas[1] (L/day)	Cumulative gas production[1] (L)	Gas Composition		Cumulative[1] CH_4 production (L)
								CO_2 (%)	CH_4 (%)	
1	394.6	25.4	1023.5	17.1	401.3	364.7	364.7	39.6	60.4	220.1
2	413.7	23.3	1023.0	18.1	421.2	384.8	749.5	39.8	60.2	451.9
3	183.7	25.3	1021.5	19.0	187.2	169.5	919.0	37.4	62.6	558.0
4	327.4	25.4	1031.4	19.1	333.6	304.9	1223.9	38.2	61.8	746.5
5	380.6	27.6	1020.5	28.1	391.4	348.1	1572.0	37.5	62.5	964.0
6	129.9	28.9	1020.0	34.7	134.5	118.2	1690.3	39.9	60.1	1035.1
7	117.9	29.7	1018.5	24.8	120.8	106.9	1797.2	40.0	60.0	1099.2
8	83.7	28.4	1018.5	24.7	85.8	76.2	1873.4	40.5	59.5	1144.5
9	118.3	28.4	1016.0	26.3	121.4	107.4	1980.8	39.7	60.3	1209.3
10	98.4	28.9	1017.0	25.6	100.9	89.3	2070.1	39.7	60.3	1263.2
11	98.7	30.3	1018.0	26.4	101.3	89.3	2159.4	38.5	61.5	1318.1
12	96.4	29.5	1019.0	29.0	99.2	87.5	2246.9	37.7	62.3	1372.6
13	94.6	29.5	1017.5	29.9	97.5	85.7	2332.6	38.1	61.9	1425.7
14	50.5	28.5	1016.5	32.3	52.2	45.9	2378.5	37.7	62.3	1454.3
15	58.1	29.4	1019.5	28.2	59.8	52.8	2431.3	36.5	63.5	1487.8
16	21.1	27.2	1020.0	21.6	21.6	19.3	2450.6	36.7	63.3	1500.1

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

Table C-11: Biogas production in Fresh waste reactor SEBAC cycle I

Run time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar*(mb)*	Vapour Pressure Mllibar*(mb)*	Dry volume of gas) (L/day	Volume of gas[1] (L/day)	Cumulative gas production[1] (L)	Gas Composition		Cumulative[1] CH4 production (L)
								CO_2 (%)	CH_4 (%)	
1	40.4	25.4	1023.5	17.1	41.1	37.3	37.3	92.5	7.50	2.80
2	143.2	23.3	1023.0	18.1	145.8	133.2	170.5	84.03	15.97	24.07
3	109.9	25.3	1021.5	19.0	112.0	101.4	271.9	63.61	30.60	55.10
4	406.8	25.4	1019.5	19.1	414.6	374.5	646.4	53.53	36.47	191.67
5	422.0	27.6	1020.5	28.1	433.9	386.0	1032.4	51.31	40.14	346.61
6	169.4	28.9	1020.0	34.7	175.4	154.2	1186.6	50.64	43.13	413.12
7	100.0	29.7	1018.5	24.8	102.5	90.7	1277.3	45.30	50.70	459.08
8	200.8	28.4	1018.5	24.7	205.8	182.8	1460.1	42.26	55.89	561.26
9	219.5	28.4	1016.0	26.3	225.3	199.4	1659.4	37.55	57.74	676.37
10	201.2	28.9	1017.0	25.6	206.4	182.6	1842.1	37.03	62.45	790.41
11	276.6	30.3	1018.0	26.4	284.0	250.1	2092.2	37.05	62.97	947.92
12	102.6	29.5	1019.0	29.0	105.6	93.1	2185.3	38.14	62.95	1006.54
13	146.0	29.5	1017.5	29.9	150.4	132.3	2317.6	39.67	61.86	1088.39
14	83.5	28.5	1016.5	32.3	86.2	75.8	2393.5	39.67	60.33	1134.15
15	150.2	29.4	1019.5	28.2	154.5	136.4	2529.9	38.22	61.78	1218.44
16	116.8	27.2	1020.0	21.6	119.3	106.9	2636.8	39.80	60.2	1282.80
17	86.4	26.5	1020.0	21.5	88.3	79.3	2716.1	39.91	60.09	1330.44
18	73.9	27.0	1019.5	22.0	75.53	67.7	2783.8	38.68	61.32	1371.94
19	66.9	27.0	1019.5	27.0	68.72	61.3	2845.0	39.82	60.18	1408.80
20	184	27.5	1019.0	26.6	188.9	168.1	3013.1	39.12	60.88	1511.14
21	134	27.8	1019.5	21.5	136.9	122.4	3135.5	38.60	61.40	1586.28
22	56.7	27.1	1019.5	20.3	57.9	51.9	3187.4	40.10	59.90	1617.36
23	83.5	26.4	1019.0	20.1	85.2	76.6	3264.0	40.18	59.82	1663.17
24	79.5	24.6	1021.0	17.3	80.9	73.5	3337.5	40.09	59.91	1707.19
25	89.5	24.5	1023.0	18.0	91.1	82.9	3420.4	40.12	59.88	1756.85
26	46.6	24.8	1023.5	22.3	47.6	43.2	3463.5	39.77	60.23	1782.84
27	14	22.9	1024.0	17.8	14.2	13.1	3476.6	39.67	60.33	1790.71

Table C- 12: Biogas production in Stabilized reactor SEBAC cycle II

Run Time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar*(mb)*	Vapour Pressure Mllibar*(mb)*	Dry volume of gas (L/day)	Volume of gas^1 (L/day)	Cumulative gas production^1 (L)	Gas Composition		Cumulative^1 CH_4 production (L)
								CO_2 (%)	CH_4 (%)	
1	84.3	23.7	1021.0	25.3	86.4	80.1	80.13	39.77	60.23	48.27
2	132.2	24.4	1019.0	19.6	134.8	124.4	204.5	38.18	61.82	125.18
3	156.5	25.9	1019.5	25.8	160.6	147.5	352.0	38.07	61.93	216.54
4	215.3	26.8	1019.0	25.6	220.8	202.2	554.2	37.98	62.02	341.94
5	205.1	26.8	1020.5	30.0	211.3	193.8	748.0	38.05	61.95	461.97
6	195.4	26.3	1020.0	35.2	202.4	185.8	933.8	37.68	62.32	577.75
7	159.5	27.5	1019.0	27.1	163.9	149.7	1083.5	37.55	62.45	671.22
8	143.8	28.1	1019.3	28.0	147.9	134.8	1218.3	37.55	62.45	755.42
9	132.1	27.8	1017.6	29.1	136.0	123.9	1342.2	36.68	63.32	833.89
10	102.3	27.7	1017.5	21.0	104.5	95.2	1437.4	36.13	63.87	894.70
11	96.2	26.9	1018.5	22.9	98.4	90.0	1527.4	36.47	63.53	951.89
12	87.7	26.5	1018.5	30.6	90.4	82.8	1610.3	35.66	64.34	1005.18
13	75.8	27.0	1018.0	29.9	78.1	71.4	1681.6	35.44	64.56	1051.26
14	49.4	27.3	1018.5	23.7	50.6	46.2	1727.8	35.35	64.65	1081.13
15	45.3	26.1	1020.0	23.7	46.4	42.6	1770.4	34.98	65.02	1108.83
16	23.2	24.4	1023.0	20.5	23.7	21.9	1792.4	34.79	65.21	1123.14

Table C-13: Biogas production in Fresh waste reactor SEBAC cycle II

Run Time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar*)* *(mb)*	Vapour Pressure Mllibar *(mb)*	Dry volume of gas (L/day)	Volume of gas[1] (L/day)	Cumulative gas production[1] (L)	Gas Composition		Cumulative[1] CH_4 production (L)
								CO_2 (%)	CH_4 (%)	
1	190.4	23.7	1021.0	25.3	195.2	181.0	181.0	89.25	10.75	19.46
2	235.4	24.4	1019.0	19.6	240.0	221.5	402.5	77.60	22.40	69.08
3	259.1	25.9	1019.5	25.8	265.8	244.2	646.7	63.61	36.39	157.96
4	309.5	26.8	1019.0	25.6	317.5	290.7	937.4	59.53	40.47	275.59
5	251.3	26.8	1020.5	30.0	258.9	237.4	1174.8	53.31	46.69	386.43
6	339.7	26.3	1020.0	35.2	351.8	323.0	1497.8	50.64	49.36	545.85
7	359.8	27.5	1019.0	27.1	369.6	337.6	1835.4	48.14	51.86	720.94
8	311.4	28.1	1019.3	28.0	320.2	292.0	2127.4	45.32	54.68	880.60
9	346.8	27.8	1017.6	29.1	357.0	325.3	2452.7	43.45	56.55	1064.57
10	362.7	27.7	1017.5	21.0	370.3	337.6	2790.2	37.13	62.87	1276.79
11	319.5	26.9	1018.5	22.9	326.8	299.0	3089.2	36.75	63.25	1465.91
12	367.5	26.5	1018.5	30.6	378.9	347.1	3436.3	36.83	63.17	1685.15
13	334.2	27.0	1018.0	29.9	344.3	314.7	3751.0	35.21	64.79	1889.05
14	234.5	27.3	1018.5	23.7	240.1	219.3	3970.4	35.57	64.43	2030.37
15	189.7	26.1	1020.0	23.7	194.2	178.4	4148.8	34.34	65.66	2147.51
16	172.4	24.4	1023.0	20.5	175.9	163.0	4311.8	33.58	66.42	2255.78
17	150	24.4	1023.5	18.5	152.8	141.6	4453.4	34.37	65.63	2348.72
18	164	25.2	1021.5	19.0	167.1	154.2	4607.6	32.23	67.77	2453.21
19	145.7	24.8	1021.5	25.4	149.4	138.1	4745.6	32.76	67.24	2546.04
20	120.4	25.1	1020.5	52.4	126.9	117.0	4862.7	33.06	66.94	2624.38
21	96.8	26.6	1020.5	22.6	99.0	90.8	4953.5	32.44	67.56	2685.74
22	45.4	27.0	1022.3	28.2	46.7	42.9	4996.3	32.25	67.75	2714.78
23	7.4	28.7	1022.0	28.5	7.6	6.9	5003.3	31.27	68.73	2719.55

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

Table C- 14: Biogas production in Stabilized reactor SEBAC cycle III

Run time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar *(mb)*	Vapour Pressure Mllibar (*mb*)	Dry volume of gas (L/day)	Volume of gas[1] (L/day)	Cumulative gas production[1] (L)	Gas Composition		Cumulative[1] CH4 production (L)
								CO_2 (%)	CH_4 (%)	
1	25.6	27.8	1021.0	21.4	26.1	23.9	23.91	34.32	65.68	15.71
2	84.3	27.4	1021.0	19.2	85.9	78.7	102.56	33.25	66.75	68.21
3	72.4	26.7	1022.5	22.4	74.0	68.0	170.59	33.11	66.89	113.71
4	132.0	28.4	1021.5	25.9	135.4	123.6	294.23	32.93	67.07	196.64
5	151.2	28.3	1022.0	26.3	155.2	141.8	436.03	32.63	67.37	292.17
6	246.4	28.8	1021.0	30.0	253.9	231.3	667.36	32.30	67.70	448.78
7	215.9	28.0	1020.5	28.0	222.0	202.7	870.09	32.01	67.99	586.62
8	199.6	23.0	1022.5	24.3	204.5	190.2	1060.34	31.99	68.01	716.00
9	184.7	27.5	1020.0	27.6	189.8	173.6	1233.91	31.59	68.41	834.74
10	153.3	28.5	1019.5	28.4	157.7	143.6	1377.54	31.44	68.56	933.22
11	120.1	29.8	1019.3	32.1	124.0	112.4	1489.98	31.04	68.96	1010.75
12	100.5	29.4	1019.5	33.0	103.9	94.3	1584.30	30.77	69.23	1076.05
13	102.8	28.8	1021.0	29.9	105.9	96.5	1680.80	30.58	69.42	1143.05
14	96.1	29.7	1020.5	32.3	99.2	90.1	1770.93	30.28	69.72	1205.88
15	87.5	29.5	1018.5	29.6	90.1	81.7	1852.66	30.11	69.89	1263.00
16	76.0	30.4	1018.0	31.1	78.4	70.9	1923.51	29.68	70.32	1312.82
17	72.9	30.6	1017.5	30.7	75.2	67.9	1991.37	29.13	70.87	1360.92
18	56.6	29.6	1017.0	26.0	58.1	52.6	2043.95	28.93	71.07	1398.29
19	29.4	29.3	1017.0	28.8	30.3	27.4	2071.37	29.07	70.93	1417.74

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

Table C-15: Biogas production in Fresh waste reactor in SEBAC cycle III

Run time (days)	Volume of gas produced (L/day)	Temperature °C	Ambient Pressure Millibar *(mb)*	Vapor Pressure Mllibar *(mb)*	Dry volume of gas (L/day)	Volume of gas[1] (L/day)	Cumulative gas production[1] (L)	Gas Composition		Cumulative[1] CH_4 production (L)
								CO_2 (%)	CH_4 (%)	
1	277.4	27.8	1021.0	21.4	283.3	259.1	259.1	80.07	19.93	51.64
2	428.1	27.4	1021.0	19.2	436.3	399.4	658.5	71.18	28.82	166.76
3	528.5	26.7	1022.5	22.4	540.3	496.6	1155.1	63.12	36.88	349.90
4	590.5	28.4	1021.5	25.9	605.9	553.1	1708.2	56.67	43.33	589.56
5	577.4	28.3	1022.0	26.3	592.7	541.5	2249.7	47.47	52.53	874.00
6	576.3	28.8	1021.0	30.0	596.8	534.9	2884.6	41.69	58.31	1244.24
7	513.2	28.0	1020.5	28.0	527.7	481.9	3366.5	40.62	59.38	1530.39
8	490.7	23.0	1022.5	24.3	502.6	467.7	3834.2	39.85	60.15	1811.71
9	398.1	27.5	1020.0	27.6	409.2	374.1	4208.3	38.39	61.61	2042.20
10	278.6	28.5	1019.5	28.4	286.6	261.0	4469.4	37.46	62.54	2205.45
11	216.1	29.8	1019.3	32.1	223.1	202.3	4671.7	36.8	63.2	2333.32
12	177.8	29.4	1019.5	33.0	183.7	166.9	4838.5	36.25	63.75	2439.69
13	163.4	28.8	1021.0	29.9	168.3	153.4	4991.9	35.11	64.89	2539.23
14	149.6	29.7	1020.5	32.3	154.5	140.3	5132.2	34.94	65.06	2630.51
15	120.5	29.5	1018.5	29.6	124.1	112.6	5244.8	34.45	65.55	2704.29
16	119.5	30.4	1018.0	31.1	123.3	111.4	5356.2	34.03	65.97	2777.78
17	118	30.6	1017.5	30.7	121.7	109.8	5466.0	33.47	66.53	2850.86
18	84.6	29.6	1017.0	26.0	86.8	78.6	5544.6	32.84	67.16	2903.64
19	70.0	29.3	1017.0	28.8	72.0	65.3	5609.9	31.11	68.89	2948.62
20	62.9	29.5	1018.0	34.4	65.1	59.0	5668.9	29.92	70.08	2989.97
21	24.1	30.8	1017.0	35.6	25.0	22.5	5691.4	30.99	69.01	3005.51

[1] Volume at STP (0° C, 101.325 *kPa* (1013.35 *mb*)

Appendix D: Pilot scale -Continuous anaerobic digestion

Table D-a: Leachate characteristics during start-up

Run time (Days)	pH	Alkalinity (mg/L as CaCO3)	VFA (mg/L)	DOC (mg/L)	NH4-N (mg/L)	TCOD (mg/L)	SCOD (mg/L)
1	6.84		2007	4470	784	13343	11461.5
2	6.77		3271	4980	770	15962	12146.3
3	6.63	5400	3183	5620	784	17399	15611.1
4	6.29	6300	3498	5730	868	15829	14692.3
5	6.62	7000	3693	6050	882	18389	15921.1
6	6.45	7000	4335	8070	980	20645	17170.7
7	6.53	7100	4951	8610	994	19889	17095.2
8	6.68	7200	4478	7180	1022	23805	18767.4
9	6.69	7100	2799	7040	1036	23460	22076.9
10	6.87	7400	2247	7150	1064	21933	17439.0
11	7.01	8500	1648	7070	1134	21360	17675.0
12	7.29	8900			1148		
13	7.40	9200	1599	6390	1164	23239	18948.7
14	7.47	9300	1776	6830	1204	22032	17973.7
15	7.71	9600	1818	6920	1302	20657	16878.0
16	7.78	9600	2126	6390	1204	19568	15585.4
17	7.85	9800	1765	5250	1316	13227	11024.4
18	7.98	9900	2105	4520	1330		
19	7.89	10000	2395	5170	1316		

Table D-b: Leachate characteristics during batch and continuous feeding

Run time (Days)	pH	Alkalinity (mg/L as CaCO3)	VFA (mg/L)	DOC (mg/L)	NH_4-N (mg/L)	Feeding mode
19	**7.89**	**10000**	**2395**	**5170**	**1316**	**Batch**
20	7.98	10400	2391	6480	1288	
21	7.96	10400	2812	6700	1330	
22	7.97	10400	1811	6350	1316	
23	7.98	10300	1588	5870	1344	
24	7.77	10200	1731	6540	1330	
25	7.74	10500	1555	6390	1288	
26	7.85	10100	1763	6470	1358	
27	7.74	10400	2249	6600	1316	
28	7.77	10300	1637	5780	1288	
29	7.87	10200	1495	6040	1302	
30	7.86	10200	1823	5220	1316	
31	7.87	10100	1644	6100	1288	
32	7.93	9900	1318	5900	1316	
33	7.98	10000	1065	5500	1330	
34	7.89	10100	1889	4980	1344	
35	7.89	10200	1877	5480	1288	
36	7.99	10400	1936	5350	1302	
37	7.93	10300	21096	5320	1330	
38	7.91	10100	2770	4950	1288	
39	7.93	10200	2514	5850	1358	
40	7.84	10000	2131	4890	1330	
41	7.89	10300		5780	1288	
42	7.86	10200	2112	5490	1274	
43	7.98	**10200**	4973	**6140**	**1260**	**Continuous (Loading 1)**
44	7.86	10100	5265	6750	1274	
45	7.98	10000	5332	6200	1316	
46	7.93	9900	5150	5920	1372	
47	7.98	10000	5461	6580	1358	
48	7.82	9900	5729	6820	1386	
49	7.83	9800	4950	6600	1428	
50	7.85	10000	5751	7100	1456	
51	7.83	9700	5405	6592	1330	
52	7.80	9800	6252	7270	1344	
53	7.89	9600	5820	6690	1414	
54	7.91	9800	5005	6030	1540	
55	7.98	9700	4880	5810	1526	
56	7.99	9800	4665	6220	1512	
57	8.01	9700	5295	6380		
58	8.09	10000	5670	6750	1498	
59	7.98	9900	5270	6200		

60	7.99	9800	4795	5920	1484	
61	7.89	10000	5396	6580		
62	7.98	9700	5865	6820	1414	
63	7.77	9800	5394	6200		
64	7.86	9600	5287	6370	1540	
65	7.84	9800	4588	6200		
66	7.88	9700	5461	6350	1526	
67	7.79	9800	5133	5900		
68	7.84	9700	4631	5580	1582	
69	7.85	10000	5124	6100		
70	7.88	9800	5899	6940	1512	
71	7.87	9900	5661	6820		
72	7.86	9600	4922	5860	1456	
73	8.01	10000	5500	6470		
74	7.99	9800	4905	6540		
75	**7.89**	**9900**	5592	**6820**	**1484**	**Continuous (Loading 2)**
76	7.93	9600	5655	6500		
77	7.93	9800	5096	6140		
78	7.85	9700	5015	5970	1540	
79	7.89	9800	5831	6860		
80	7.86	9700	4784	5980		
81	7.99	9900	5065	6030	1512	
82	7.83	9800	4696	5870		
83	7.87	9900	4965	6130		
84	7.89	9600	5494	6700	1526	
85	8.01	9700	5461	6350		
86	7.98	9800	5620	6460		
87	7.99	9600	4872	5870	1610	
88	7.83	10000	5586	6650		
89	7.86	9800	5117	5950		
90	7.86	9900	5698	6550	1624	
91	7.99	9900	5428	6540		
92	7.83	9800	5368	6390		
93	7.87	9900	5500	6470	1596	
94	7.83	9600	5478	6600		
95	7.85	9700	5443	6480		
96	7.81	9800	5780	6800	1582	
97	**7.84**	**9900**	**5783**	**7140**		**Continuous (Loading 3)**
98	7.82	9800	6052	7380		
99	7.80	9900	6595	7580	1526	
100	7.63	9600	6540	7880		
101	7.64	9700	5846	6960		
102	7.73	9900	6324	7440	1542	
103	7.61	9800	5910	7120		
104	7.82	9900	5872	6990		

105	7.81	9400	6595	7580	1554	
106	7.73	9600	5959	7180		
107	7.68	9700	6073	7230		
108	7.85	9800	6171	7260	1596	
109	7.57	9600	6574	7920		
110	7.53	9800	6628	7890		
111	7.72	9700	6664	7840	1610	
112	7.54	9500	5994	6970		
113	7.73	9600	6289	7670		
114	7.58	9800	6682	7680	1554	
115	**7.56**	**9500**	**6470**	**7890**		**Continuous (Loading 4)**
116	7.49	9100	6880	8000		
117	7.61	9600	7238	8320	1582	
118	7.45	8900	6806	8200		
119	7.42	9100	7451	8870		
120	7.38	9000	7310	8600	1568	
121	7.39	8900	6552	8400		
122	7.32	8800	7543	9120		
123	7.45	8800	7380	9000	1596	Unfed
124	7.46	9200	6682	7920		Unfed
125	7.68	9300	6470	7890		Unfed
126	7.75	9600	6289	7840	1554	Unfed
127	7.78	9700	5646	6970		
128	7.81	9600	5972	7670		
129	7.79	9800	6595	7680	1554	
130	7.78	9700	5959	6990		
131	7.81	9600	6073	7230	1582	
132	7.82	9700	6171	7260		
133	7.79	9700	6880	7670	1596	
134	7.81	9600	6838	7680		

Table D-1: Biogas production and composition during start-up and batch feeding

Run time (days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Remarks
			% CH_4	% CO_2	
1	130.0	130.0	0.6	99.4	Start-up
2	124.1	254.1	14.4	85.6	
3	112.1	366.2	21.39	78.61	
4	152.8	519.0	24.97	75.03	
5	116.9	635.9			
6	177.6	813.5	27.40	72.6	
7	107.5	921.0	35.87	64.13	
8	119.5	1040.5	49.65	50.35	
9	159.7	1200.2	50.25	49.75	
10	199.7	1399.9			
11	214.0	1613.9	53.45	46.55	
12	211.8	1825.7	57.08	42.92	
13	209.6	2035.3	59.83	40.17	
14	184.9	2220.2	60.43	39.57	
15	154.7	2374.9	60.51	39.49	
16	140.5	2515.4	62.06	38.94	
17	105.2	2620.6	64.59	39.41	
18	95.5	2716.1	58.08	41.92	
19	**89.2**	**2805.3**	**60.27**	**39.73**	**Batch feeding**
20	99.8	2905.1	60.50	39.5	
21	95.3	3000.4	58.26	41.74	
22	105.4	3105.8	56.02	43.98	
23	109.1	3214.9	59.15	40.854	
24	98.3	3313.2	57.68	42.32	
25	112.8	3426.0	58.94	41.06	
26	114.4	3540.4	56.15	43.85	
27	108.6	3649.0	59.33	40.67	
28	99.9	3748.9	58.85	41.15	
29	114.8	3863.7	57.49	42.51	
30	105.5	3969.2	59.41	40.59	
31	111.8	4081.0	59.80	40.2	
32	105.1	4186.1	59.78	40.22	
33	97.5	4283.6	58.45	41.55	
34	106.1	4389.7	58.20	41.8	
35	114.1	4503.8	58.90	41.1	
36	102.3	4606.1	57.89	42.11	
37	93.7	4699.8	58.3	41.7	
38	98.0	4797.8	58.2	41.8	
39	104.0	4901.8	58.82	41.18	
40	95.5	4997.3			
41	91.8	5089.1			
42	92.0	5181.1	57.89	42.11	

Table D-2: Biogas production and composition during different feedings

Run time (days)	Daily gas production (L)	Cumulative gas production (L)	Biogas composition		Remarks
			% CH_4	% CO_2	
43	**119.4**	**5300.5**	**56.97**	**43.03**	**Loading rate 1**
44	126.3	5426.8	57.98	42.02	
45	121.3	5548.1	56.27	43.73	
46	132.3	5680.4	56.16	43.84	
47	138.1	5818.5	56.17	43.83	
48	145.6	5964.1	54.55	45.45	
49	139.8	6103.9	53.51	46.49	
50	143.6	6247.5	55.25	44.75	
51	152.9	6400.4	54.56	45.44	
52	159.5	6559.9	56.35	43.65	
53	163.3	6723.2	56.49	43.51	
54	159.6	6882.8	54.36	45.64	
55	162.3	7045.1	53.54	46.46	
56	158.2	7203.3	54.21	45.79	
57	173.6	7376.9	53.67	46.33	
58	156.6	7533.5	54.87	45.13	
59	164.3	7697.8	54.33	45.67	
60	171.2	7869.0	55.65	44.35	
61	151.3	8020.3	54.98	45.02	
62	162.1	8182.4	54.54	45.46	
63	168.2	8350.6	54.21	45.79	
64	171.1	8521.7	55.32	44.68	
65	153.6	8675.3	55.43	44.57	
66	149.1	8824.4	54.73	45.27	
67	161.3	8985.7	53.54	46.46	
68	157.8	9143.5	53.24	46.76	
69	147.3	9290.8	54.32	45.68	
70	168.2	9459.0	54.65	45.35	
71	172.5	9631.5	55.13	44.87	
72	158.1	9789.6	54.96	45.04	
73	169.1	9958.7	56.9	43.1	
74	176.7	10135.4	55.54	44.46	
75	**189.9**	**10325.3**	**56.93**	**43.07**	**Loading rate 2**
76	198.3	10523.6	54.24	45.76	
77	199.3	10722.9	54.88	45.12	
78	205.5	10928.4	54.19	45.81	
79	201.8	11130.2	53.86	46.14	
80	206.6	11336.8	53.8	46.2	
81	198.4	11535.2	53.48	46.52	
82	199.6	11734.8	53.94	46.06	
83	201.6	11936.4	52.87	47.13	
84	216.5	12152.9	54.32	45.68	
85	201.4	12354.3	52.54	47.46	
86	199.4	12553.7	53.48	46.52	

87	207.9	12761.6	51.97	48.03	
88	197.4	12959.0	52.63	47.37	
89	201.3	13160.3	54.34	45.66	
90	204.5	13364.8	53.43	46.57	
91	199.4	13564.2	52.32	47.68	
92	220.2	13784.4	53.32	46.68	
93	226.1	14010.5	52.23	47.77	
94	232.3	14242.8	51.89	48.11	
95	243.3	14486.1	52.54	47.46	
96	249.3	14735.4	51.65	48.35	
97	**246.4**	**14981.8**	**52.76**	**47.24**	**Loading rate 3**
98	239.2	15221.0	52.43	47.57	
99	247.1	15468.1	51.32	48.68	
100	249.2	15717.3	51.65	48.35	
101	253.1	15970.4	52.56	47.44	
102	261.5	16231.9	52.87	47.13	
103	252.6	16484.5	51.98	48.02	
104	249.1	16733.6	51.87	48.13	
105	265.6	16999.2	52.08	47.92	
106	247.2	17246.4	51.34	48.66	
107	258.3	17504.7	52.43	47.57	
108	261.5	17766.2	51.32	48.68	
109	267.5	18033.7	52.87	47.13	
110	263.6	18297.3	51.93	48.07	
111	268.3	18565.6	52.45	47.55	
112	265.8	18831.4	51.21	48.79	
113	269.7	19101.1	52.12	47.88	
114	273.5	19374.6	51.32	48.68	
115	**253.6**	**19628.2**	**52.31**	**47.69**	**Loading rate 4**
116	248.3	19876.5	52.32	47.68	
117	254.3	20130.8	51.21	48.79	
118	246.7	20377.5	51.05	48.95	
119	259.2	20636.7	50.32	49.68	
120	259.8	20896.5	51.93	48.07	
121	242.9	21139.4	51.45	48.55	
122	239.5	21378.9	47.67	52.33	
123	249.4	21628.3	48.45	51.55	Unfed
124	247.2	21875.5			Unfed
125	242.2	22117.7	49.34	50.66	Unfed
126	250.3	22368.0	52.32	47.68	Unfed
127	253.6	22621.6			
128	247.6	22869.2	52.54	47.46	
129	253.3	23122.5			
130	247.2	23369.7	53.32	46.68	
131	242.1	23611.8			
132	249.2	23861.0	52.32	47.68	
133	253.1	24114.1			
134	250.5	24364.6	53.23	46.77	

Appendix E

Table E-1: Solid waste characteristic of fresh and digested waste (SEBAC)

Parameters	**Unit**	**Fresh waste**	**Digested waste**
Start-up R1			
Total wet weight	kg	200	36.3
MC	%	80.6	71.6
TS	%	19.4	28.4
Total solids (TS)	kg	38.8	9.6
Volatile solids(% TS)	%	80.4	52.4
Total volatile solids(TVS)	kg	28.1	5.0
TS loss	%		75.30
VS loss	%		82.1
Cycle I			
Total wet weight	kg	200	30.5
MC	%	87.2	74.3
TS	%	12.8	25.7
Total solids (TS)	kg	25.6	7.84
Volatile solids(% TS)	%	75.4	50.5
Total volatile solids(TVS)	kg	18.2	3.96
TS loss	%		69.38
VS loss	%		78.3
Cycle II			
Total wet weight	kg	200	30.2
MC	%	88.2	73.6
TS	%	11.8	26.4
Total solids (TS)	kg	23.6	7.97
Volatile solids(% TS)	%	71.4	44.3
Total volatile solids(TVS)	kg	16.9	3.53
TS loss	%		66.22
VS loss	%		79.0
Cycle III			
Total wet weight	kg	200	29.5
MC	%	88.5	73.3
TS	%	11.5	26.7
Total solids (TS)	kg	23.0	7.88
Volatile solids(% TS)	%	81.1	46.4
Total volatile solids(TVS)	kg	18.6	3.7
%TS loss	%		66.03
%VS loss	%		80.2

Table E-2: Daily feedstock input and withdrawal (Continuous digestion)

Total wet weight input (kg/day)	Total Solid (Kg)	Total Water (Kg)	**Digested to be exited Weight (kg)**	Moisture Content (%)	Solid in Digestate (Kg)	Water in Digestate (L)	Solid in Leachate kg/L	Daily Biogas Production (L)	Weight of Biogas (kg)	Leach ate weight (kg)	**Leachate to be exicited**
5	0.55	4.45	**2.44**	90	0.24	0.37	0.098	155	0.208	4.45	**2.26**
7	0.77	6.23	**3.54**	90	0.35	0.53	0.106	209	0.31	6.23	**3.05**
9	0.99	8.01	**5.07**	90	0.51	0.76	0.136	258	0.347	8.01	**3.45**
11	1.21	9.79	**7.07**	90	0.71	1.06	0.166	250	0.336	9.79	**3.42**

Appendix- F

Table F-1: BMP data from OFMSW

Sample No.	Run time (days)	Chromatographic area of methane		Mass of methane 0.2mL		Mass of methane in Reactor (g)		Removal (g)	Cumulative mass removal (g)	Cumulative mass Proucion (g)	Cumulative Volume Proucion (mL)	Cumulative Volume Proucion at STP (mL)
		before removal	after removal	before removal	after removal	before	after					
1	1	41985	41985	7.46	7.46	0.08	0.08	0.00	0.00	0.08	125.35	114.83
2	2	92586	92586	16.44	16.44	0.18	0.18	0.00	0.00	0.18	276.42	112.28
3	3	136994	136994	24.33	24.33	0.27	0.27	0.00	0.00	0.27	409.00	244.55
4	4	191470	191470	34.00	34.00	0.37	0.37	0.00	0.00	0.37	571.65	358.13
5	5	260722	26872	46.30	4.77	0.51	0.05	0.46	0.46	0.97	778.40	497.54
6	6	92220	92220	16.38	16.38	0.18	0.18	0.00	0.46	0.64	973.50	682.31
7	7	148773	148773	26.42	26.42	0.29	0.29	0.00	0.46	0.75	1142.34	852.31
8	8	199954	199954	35.51	35.51	0.39	0.39	0.00	0.46	0.85	1295.15	980.21
9	10	260752	260752	46.31	46.31	0.51	0.51	0.00	0.46	0.97	1476.67	1108.48
10	12	322618	322618	57.29	57.29	0.63	0.63	0.00	0.46	1.09	1661.37	1266.65
11	15	409082	409082	72.65	72.65	0.80	0.80	0.00	0.46	1.26	1919.51	1421.79
12	20	573397	573397	101.83	101.83	1.12	1.12	0.00	0.46	1.58	2410.09	1786.41
13	25	669121	259272	118.83	46.04	1.31	0.51	0.80	1.26	2.57	2695.88	2082.41
14	30	353629	353629	62.80	62.80	0.69	0.69	0.00	1.26	1.95	2977.59	2329.49
15	36	427120	427120	75.85	75.85	0.84	0.84	0.00	1.26	2.10	3197.00	2556.69
16	44	491444	491444	87.28	87.28	0.96	0.96	0.00	1.26	2.22	3389.04	2742.08
17	50	502258	502258	89.20	89.20	0.98	0.98	0.00	1.26	2.24	3421.33	2794.13
18	57	519062	519062	92.18	92.18	1.02	1.02	0.00	1.26	2.28	3471.50	2878.81
19	70	532508	532508	94.57	94.57	1.04	1.04	0.00	1.26	2.30	3511.64	2886.48
20	80	559062	559062	99.28	99.28	1.09	1.09	0.00	1.26	2.35	3590.92	2906.26
21	90	561258	561258	99.67	99.67	1.10	1.10	0.00	1.26	2.36	3597.48	2954.25
22	100	569620	569620	101.16	101.16	1.12	1.12	0.00	1.26	2.38	3622.44	2938.15

SEQUENTIAL BATCH AND CONTINUOUS ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN PILOT SCALE DIGESTERS

Examination Committee: **Prof. C. Visvanathan (Chairperson)**
Prof. Ajit P. Annachhatre
Dr. Toshiya Aramaki

02/05/2006

Ms. Radha Adhikari

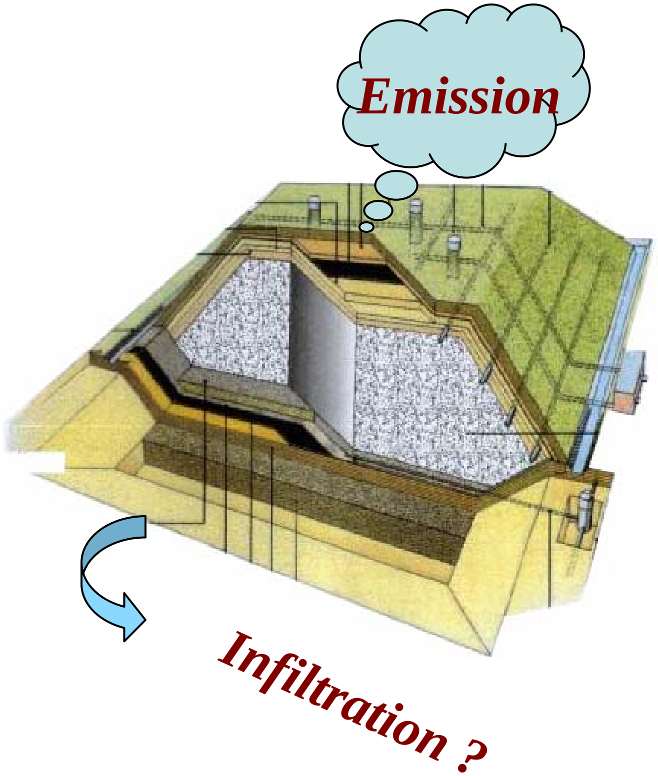
Features of Presentation

- **Introduction**
- **Problem Statement**
- **Objectives**
- **PART I: SEBAC System**
- **PART II: Continuous System**
- **Conclusions & Recommendations**

Introduction

Landfill and associate problems

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



Landfills are Necessary Evils!

Problem Statement

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

Aerobic Composting

Odor problem, Less volume reduction

net energy user

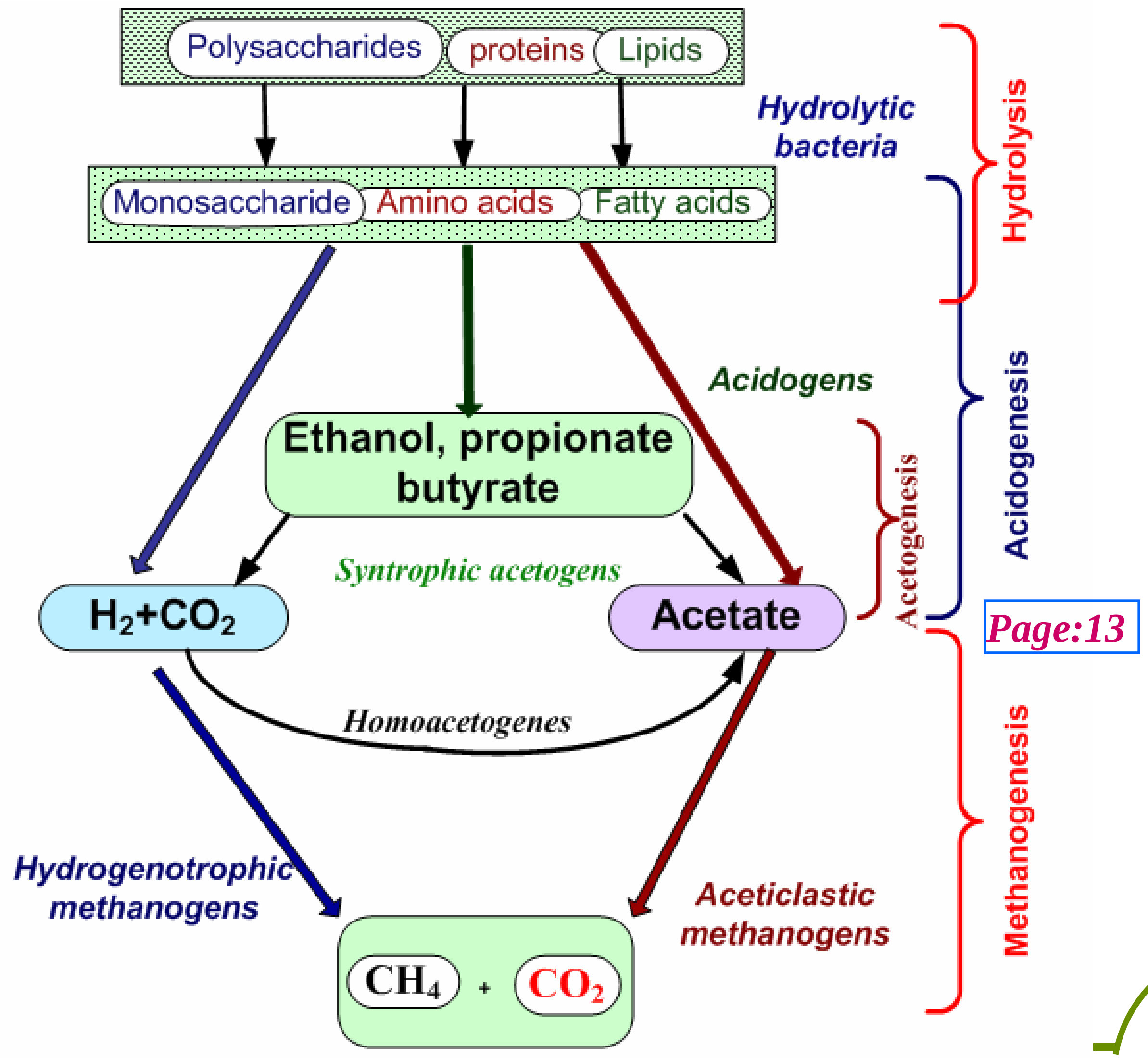
Anaerobic digestion

Less odor, more volume reduction

net energy producer

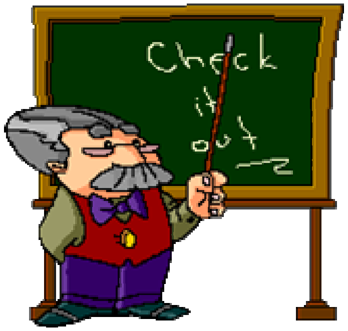
AD is Environmentally Benign !

AD Process Fundamentals



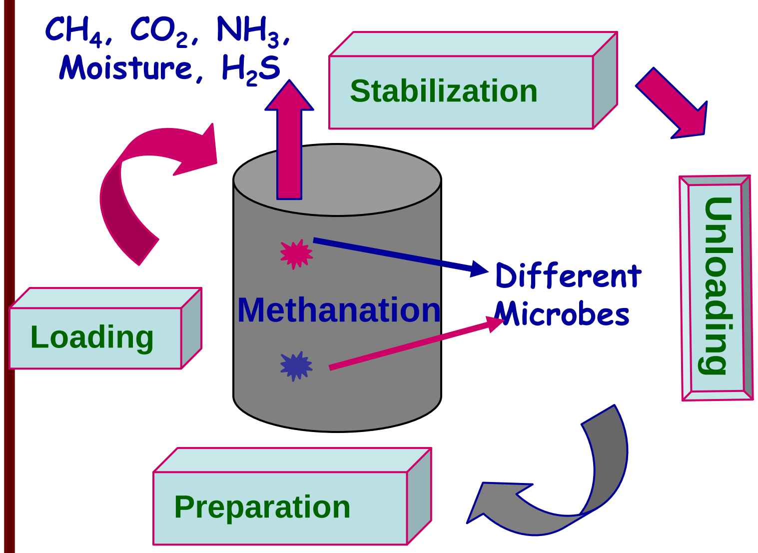
Polysaccharides
proteins
Lipids
Hydrolytic bacteria
Monosaccharide
Amino acids
Fatty acids
Acidogens
Ethanol, propionate butyrate
Syntrophic acetogens
H_2+CO_2
Acetate
Homoacetogenes
Hydrogenotrophic methanogens
Aceticlastic methanogens
CH_4 + CO_2
Hydrolysis
Acidogenesis
Acetogenesis
Methanogenesis

Page:13

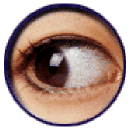


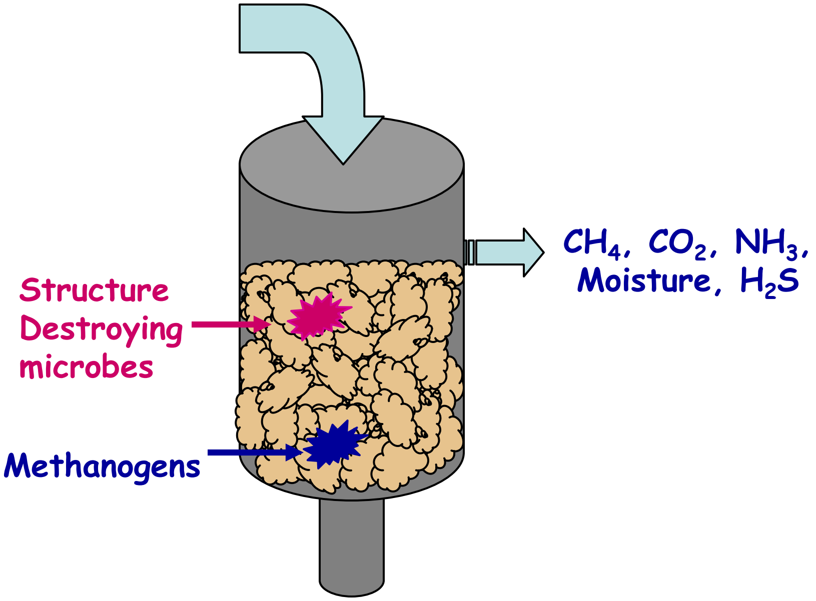
AD options: Batch Vs Continuous

Batch Anaerobic Digestion



Continuous Anaerobic Digestion





Compost Nutrient rich liquor

Technically simple, less capital intensive,

Safety measures during opening & unloading.

Requires less land area

Small feed system (large digester

Permeability Issues

Objectives

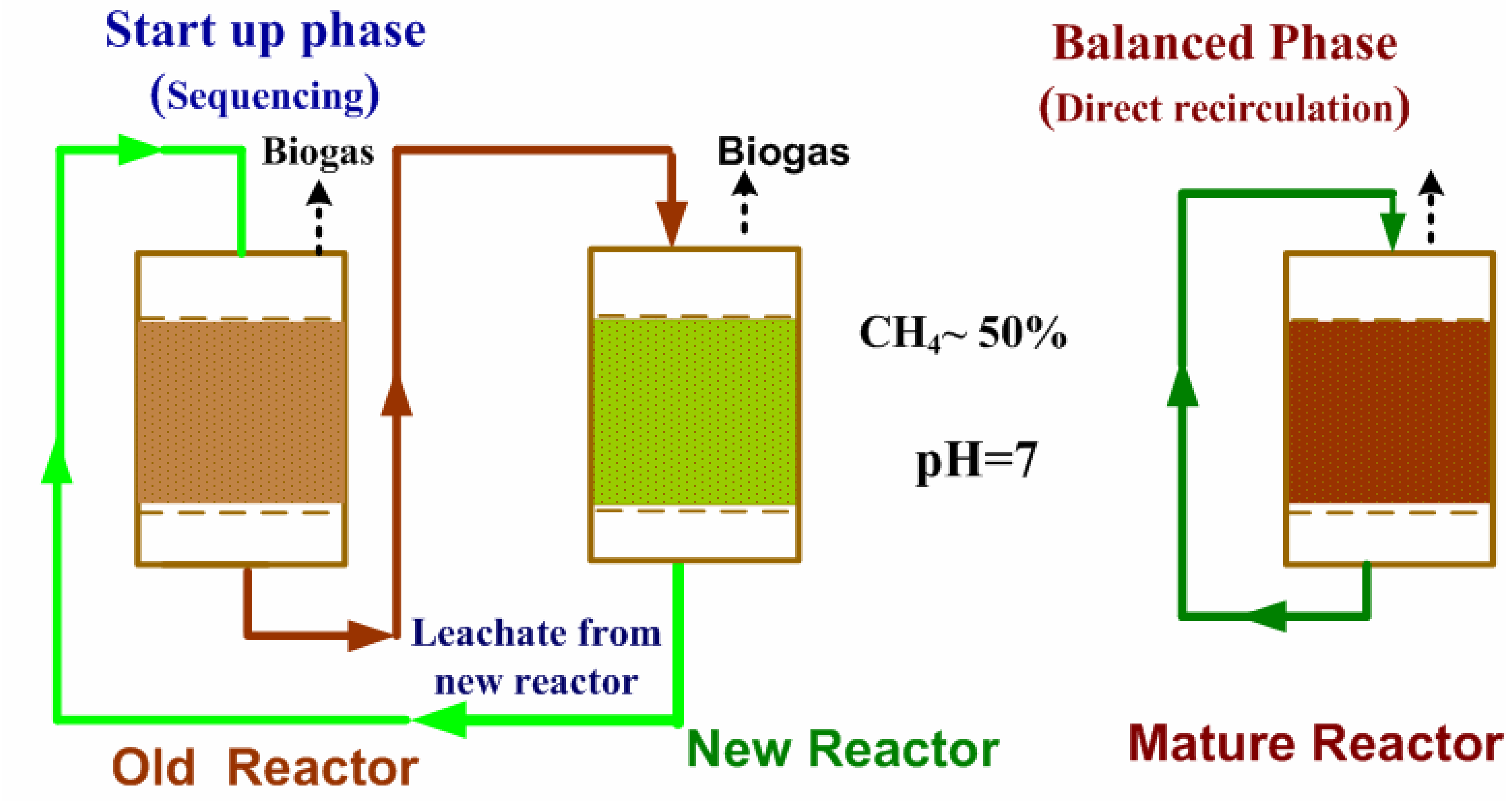
- **To investigate the performance of sequential batch anaerobic composting (SEBAC) of OFMSW in thermophilic temperature at different cross-circulation rates**

- **To design and operate a continuous system of anaerobic digestion that will be able to sustain continuous feedstock and to optimize the rate of organic loading**

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

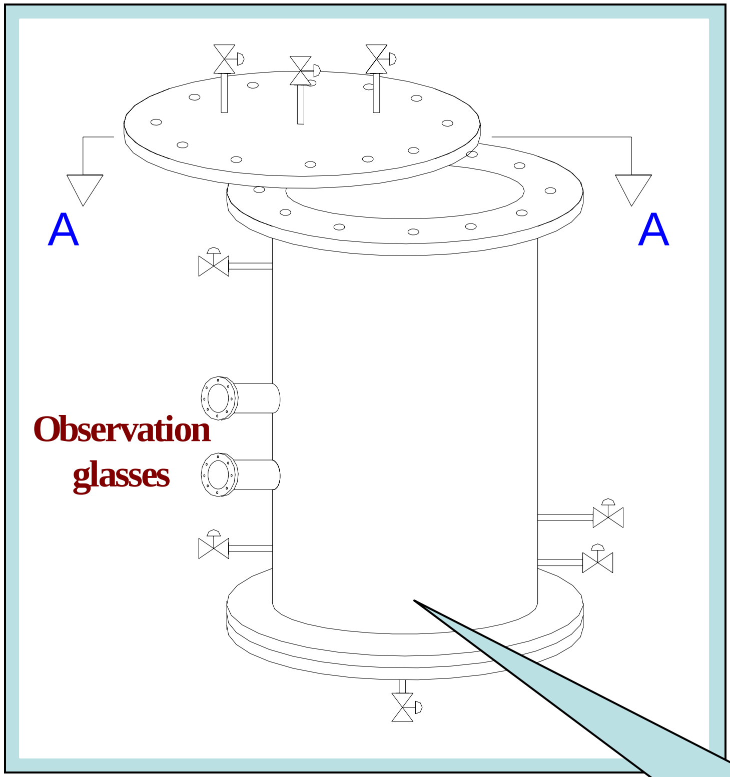
PART I: Sequential Batch Anaerobic Composting (SEBAC)

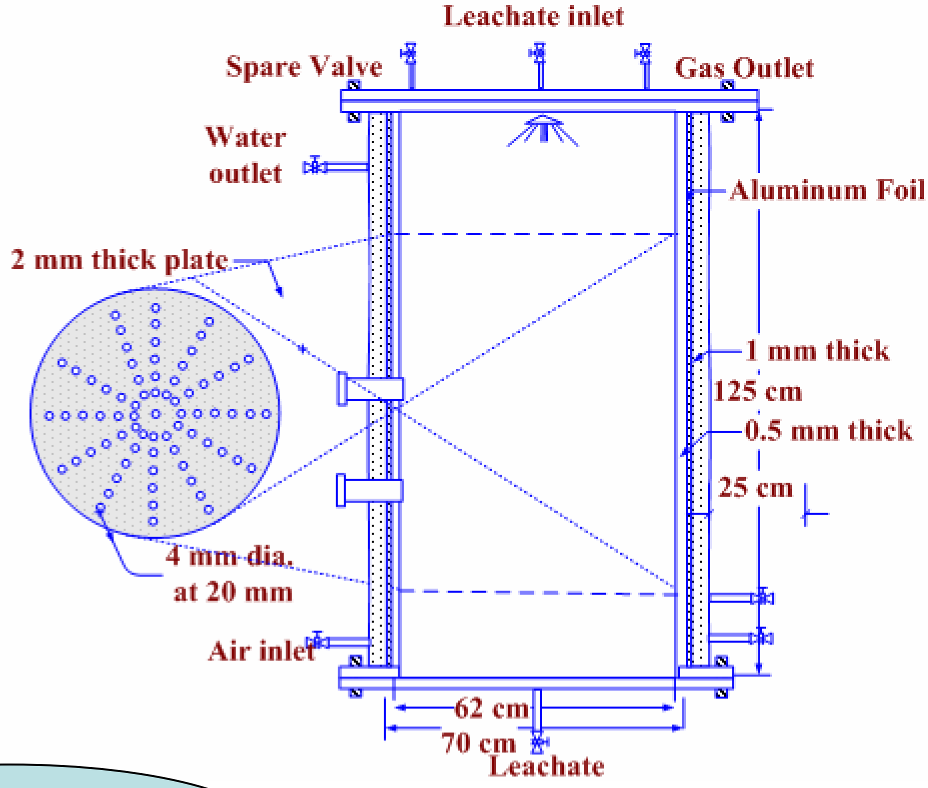
SEBAC at a glance



Page:27

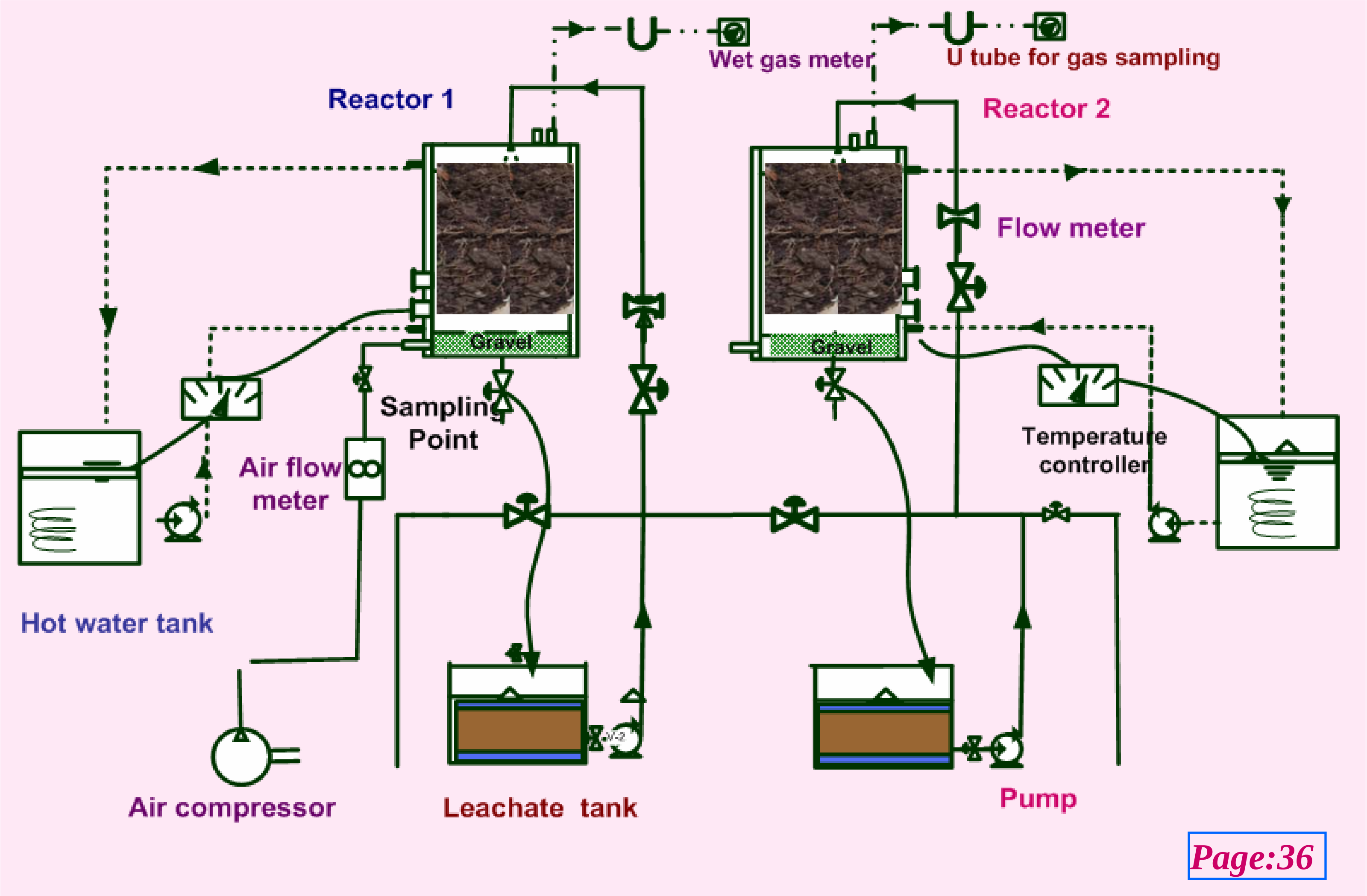
Reactor Details *Page:33*





260L Working volume

SEBAC system layout



Page:36

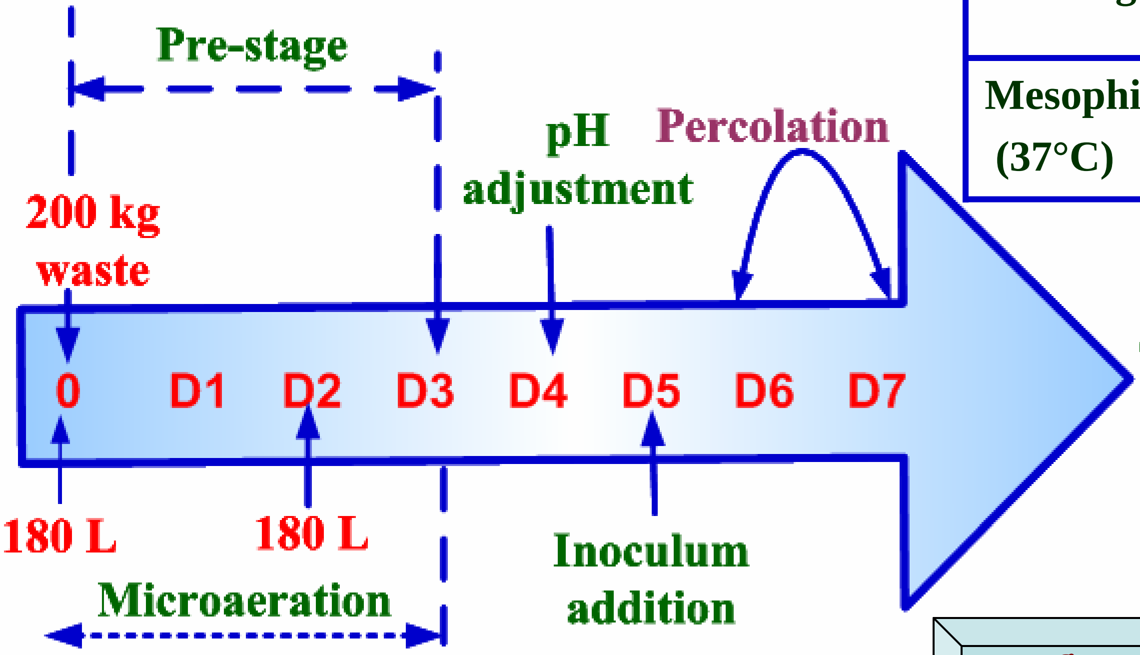
THE SEBAC SYSTEM

Stabilized reactor Preparation Run

Particle size→10mm

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

Flushing (5L/min~18m³/m³ waste/day)



Pre-stage

200 kg waste

pH adjustment

Percolation

0 D1 D2 D3 D4 D5 D6 D7

To mature phase

180 L

180 L

Microaeration

(1L/min~0.4L/kg)

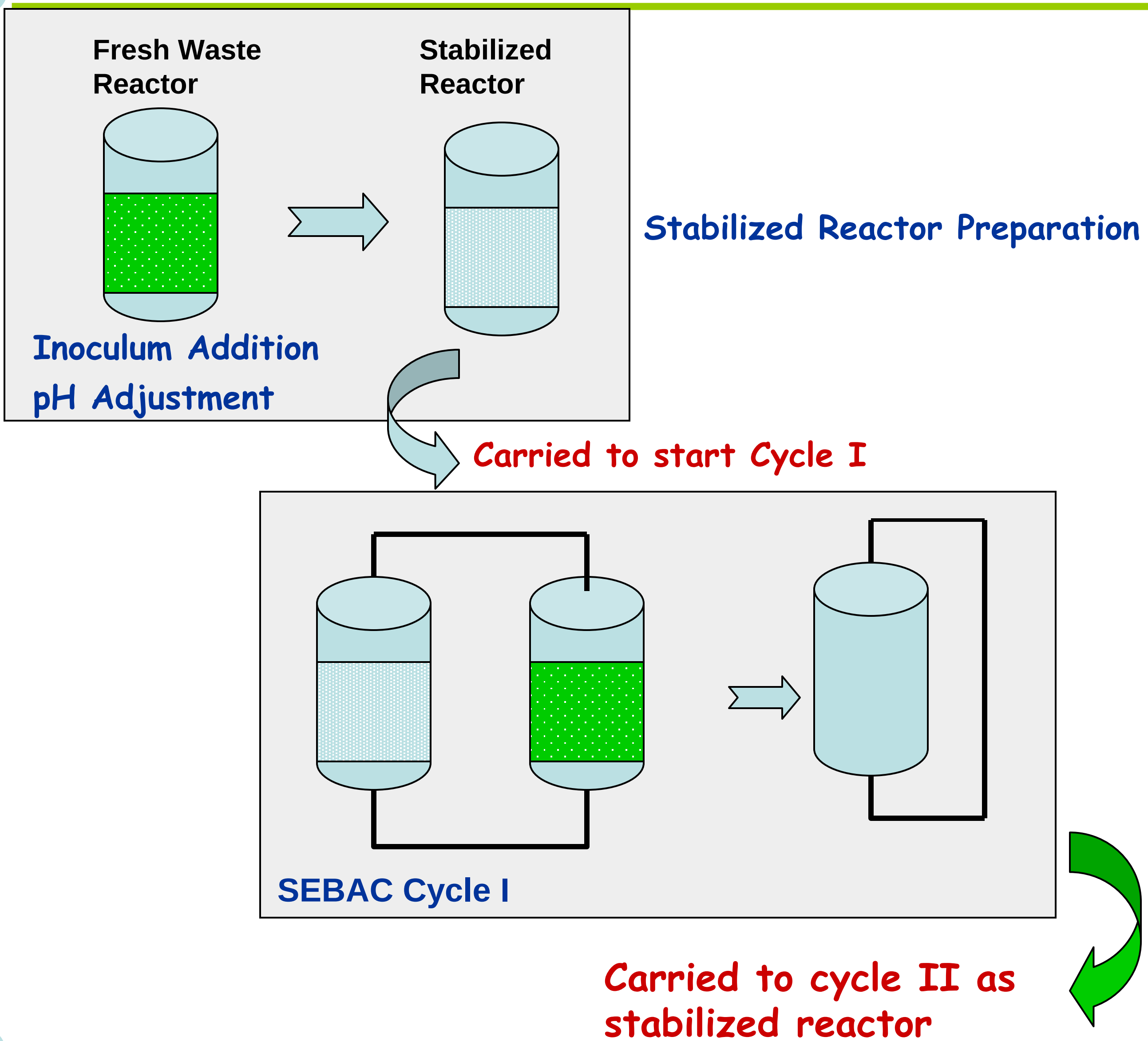
Inoculum addition

Gas Exhausted

Carried to SEBAC Cycle I

Page:35

Sequential Batch and Continuous Anaerobic Digestion of OFMSW



Fresh Waste Reactor

Stabilized Reactor

Stabilized Reactor Preparation

Inoculum Addition

pH Adjustment

Carried to start Cycle I

SEBAC Cycle I

No gas production

Carried to cycle II as stabilized reactor

SEBAC process details

Operating condition
- **Themophilic(55°C)**
- **Particle size→30mm**

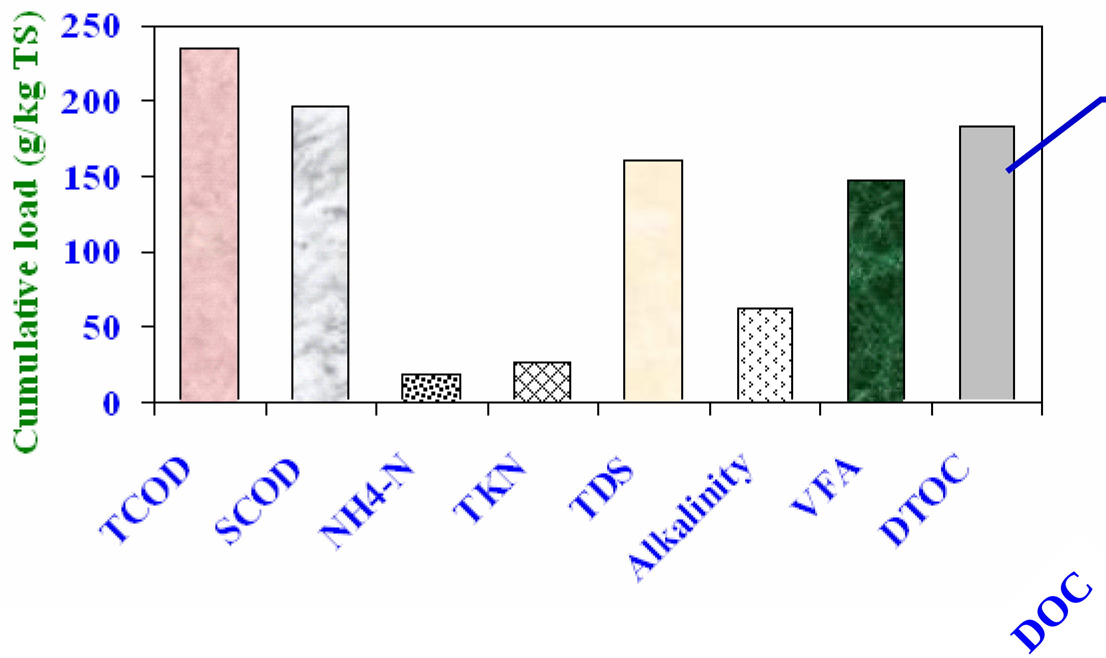
	Cross-circulation (Once daily for 30 minutes)	
Cycle	Volume	Rate (/m^3 waste.day)
Cycle I	90 L	3 L/min (0.34m^3)
Cycle II	120 L	4 L/min (0.46 m^3)
Cycle III	150 L	5 L/min (0.58 m^3)

Cycle I → pH=7 & CH4~50% (day 7)

Cycle II→ pH=7 (day5),CH4~50%(day7)

Cycle III→ pH= 7& CH4~50%(day 5)

Results: Pre-stage pollutant load removal

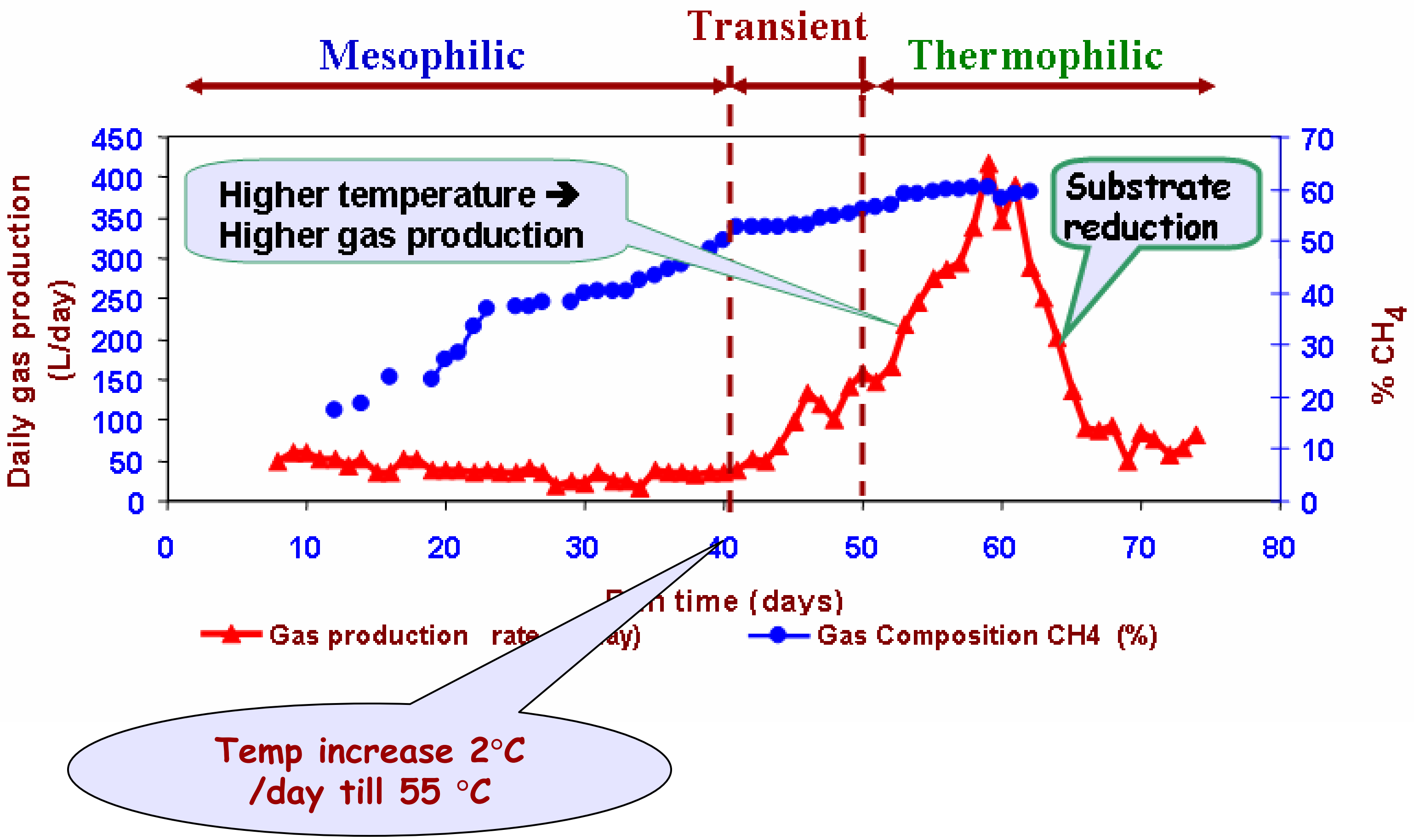


Pollutant load higher
DOC →20% higher than
thermophilic 30mm sized

Page:51

Results: Main stage biogas generation

Page:54



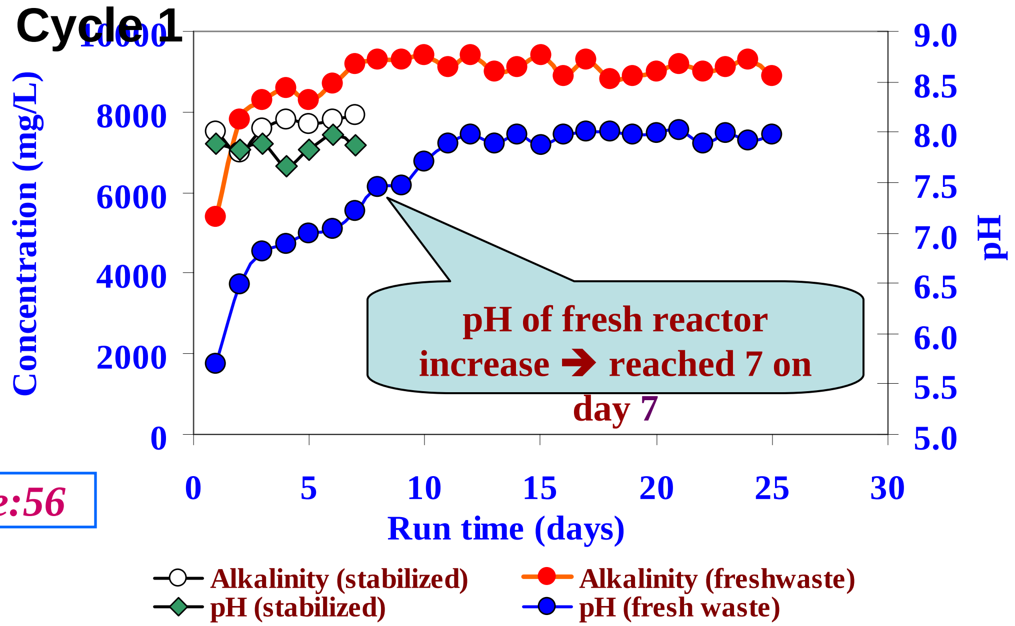
Higher temperature → Higher gas production

Substrate reduction

Temp increase 2°C /day till 55 °C

Long time inoculum acclimatization not necessary

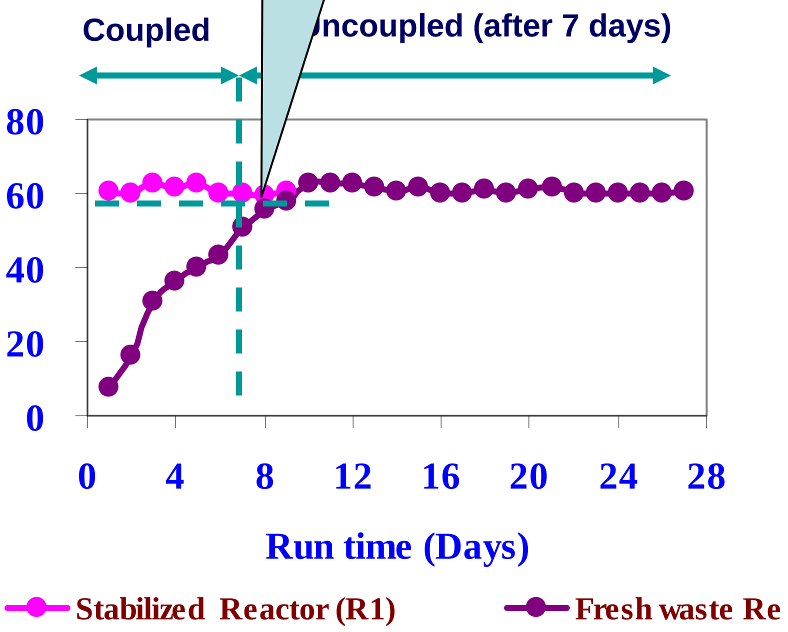
Sequential Batch and Continuous Anaerobic Digestion of OFMSW



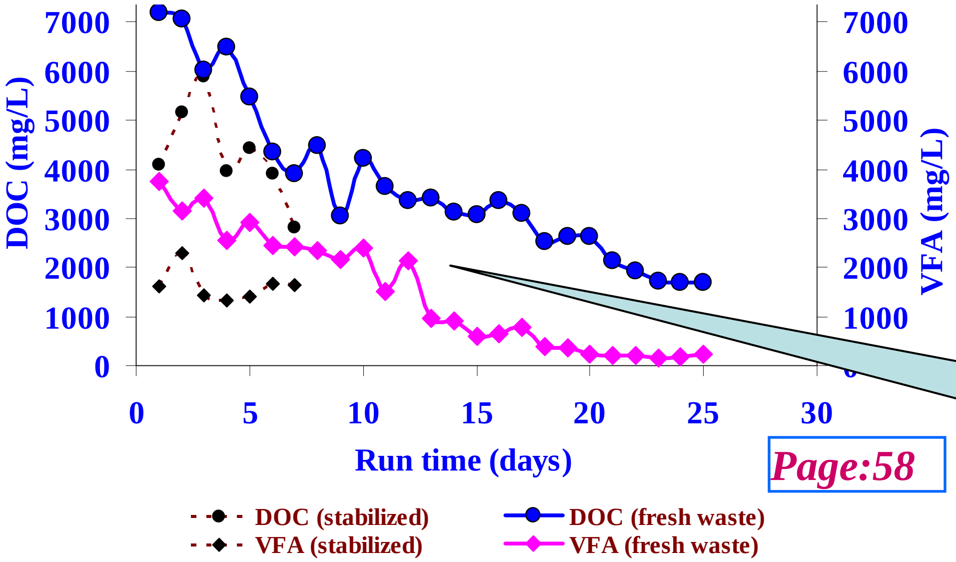
pH of fresh reactor increase ➔ reached 7 on day 7

Page:56

CH$_4$ ~50% on day7



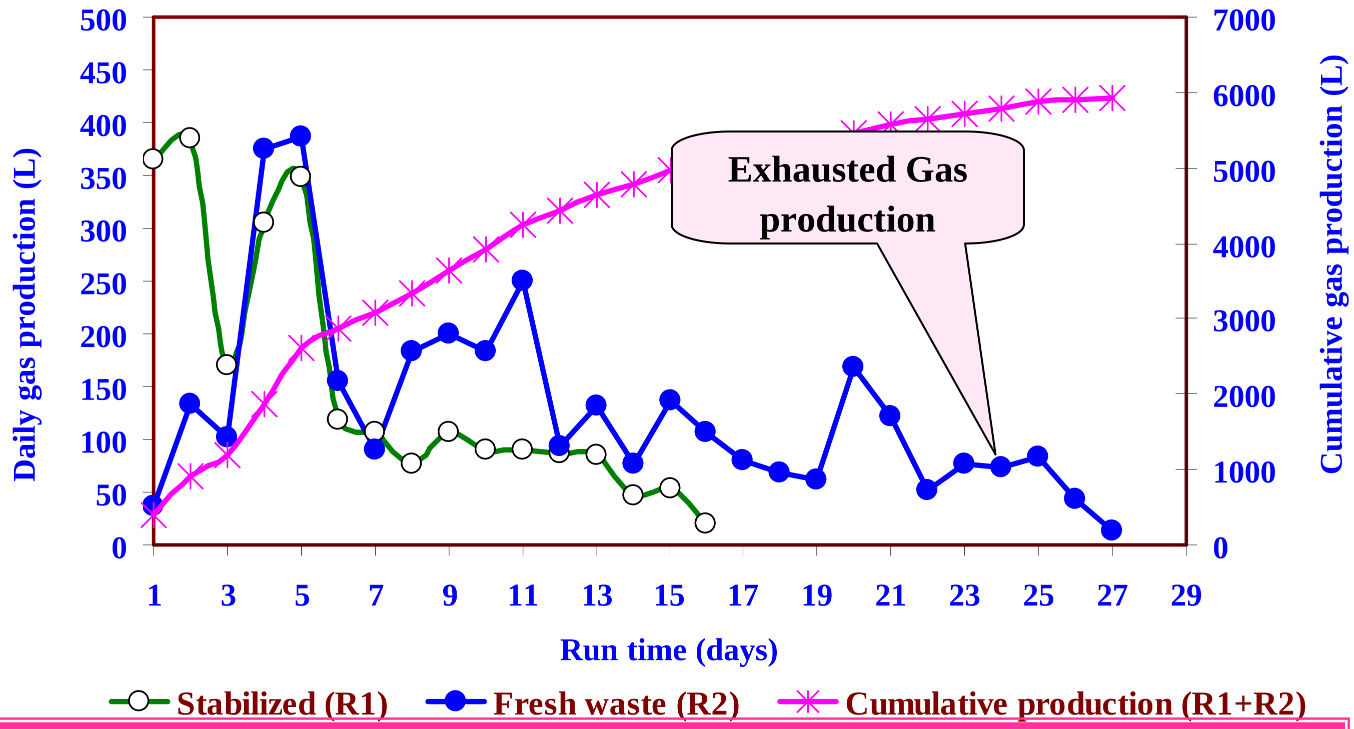
Page: 59



Page:58

Reduced VFA➔ stable performance

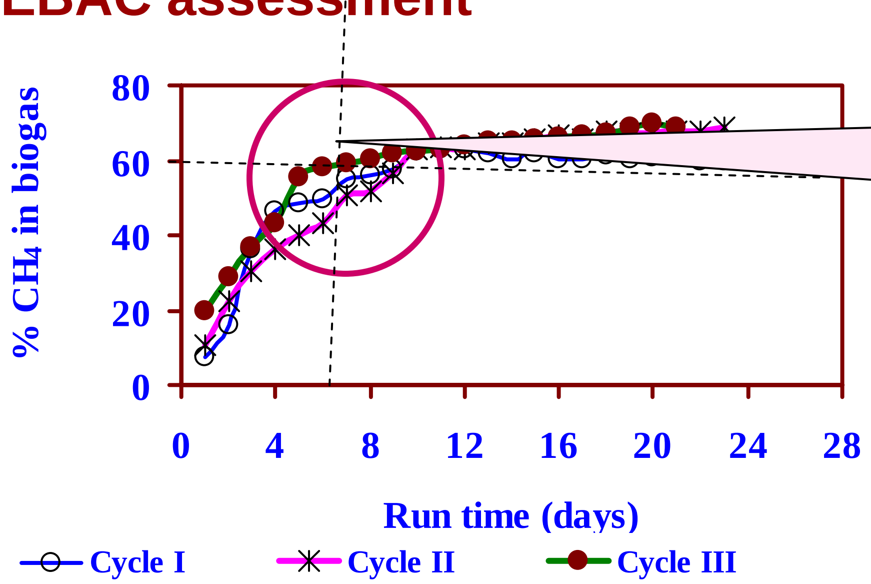
Biogas generation: SEBAC cycle I *Page:59*



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

Ms. Radha Adhikari

SEBAC assessment

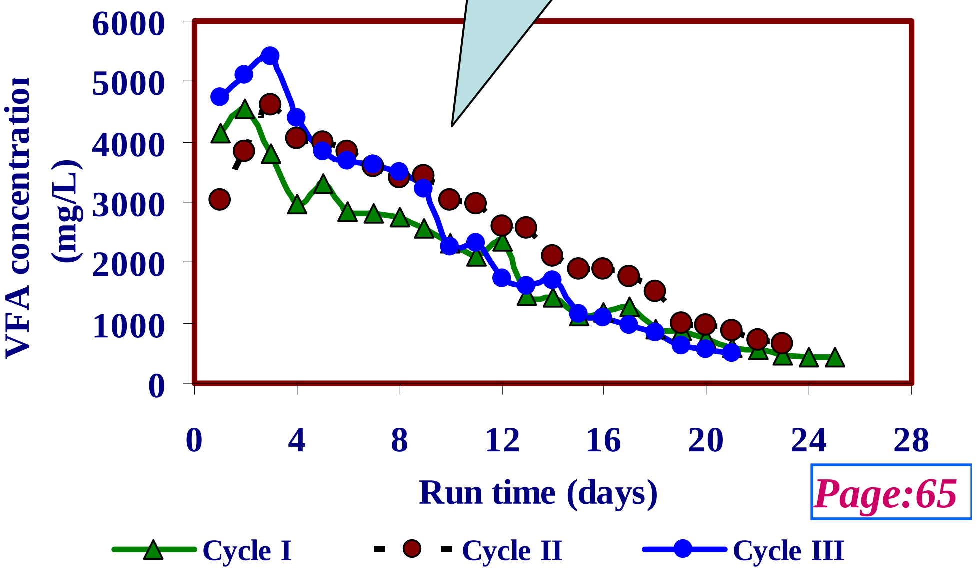


Fresh reactor remained coupled for 5 days in cycle III compared to day 7 for cycle I &II. Methane % increased faster

Page:67

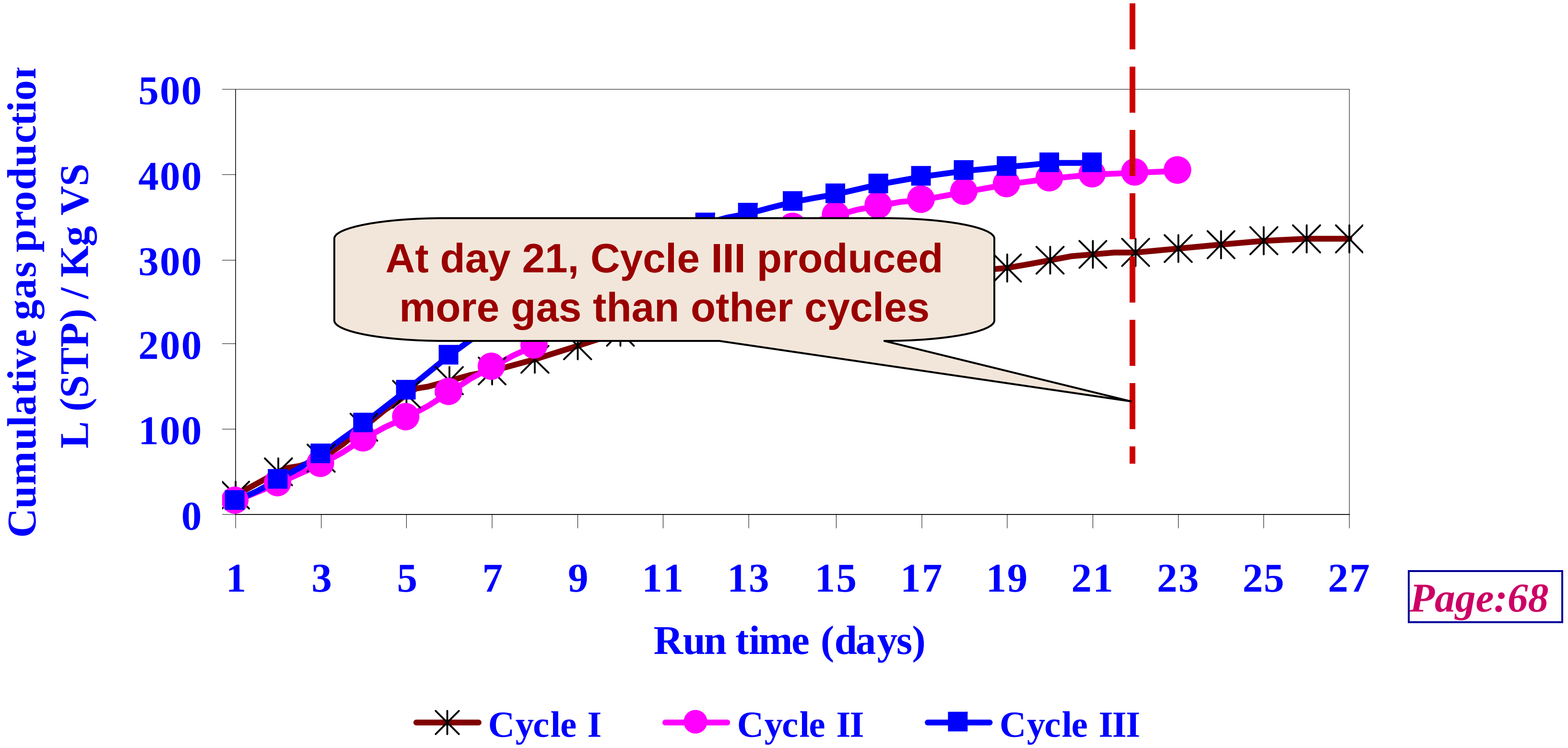
VFA dropped more rapidly in cycle III than others

Increased circulation, VFA are distributed more efficiently producing better contact with microorganism, stimulated methanogenesis activities



Page:65

SEBAC process assessment

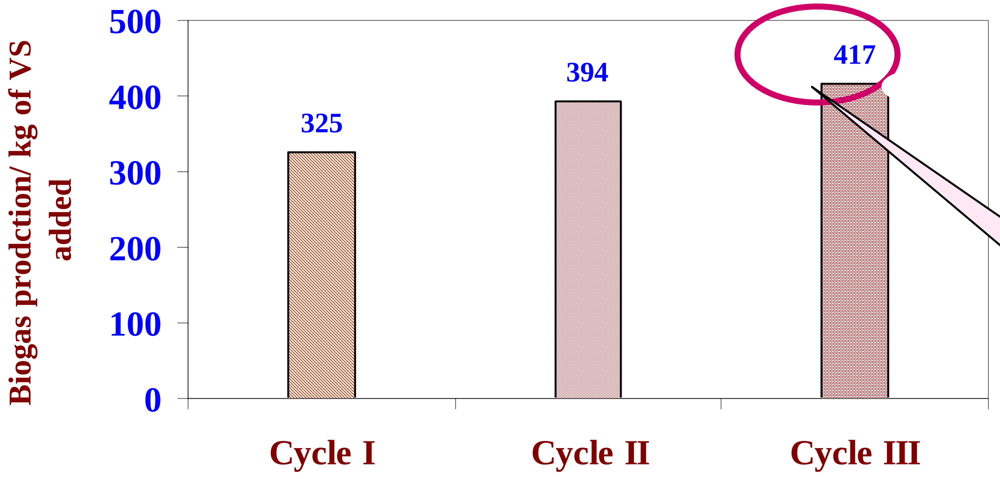


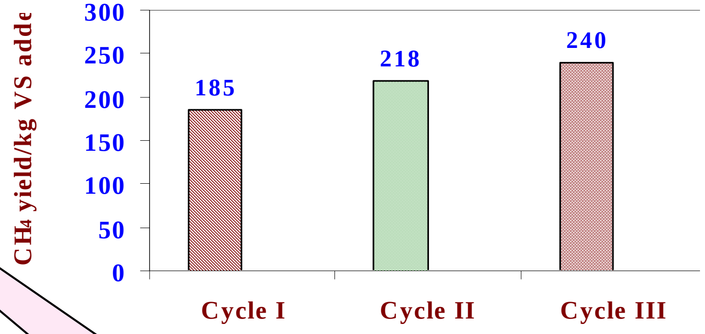
At day 21, Cycle III produced more gas than other cycles

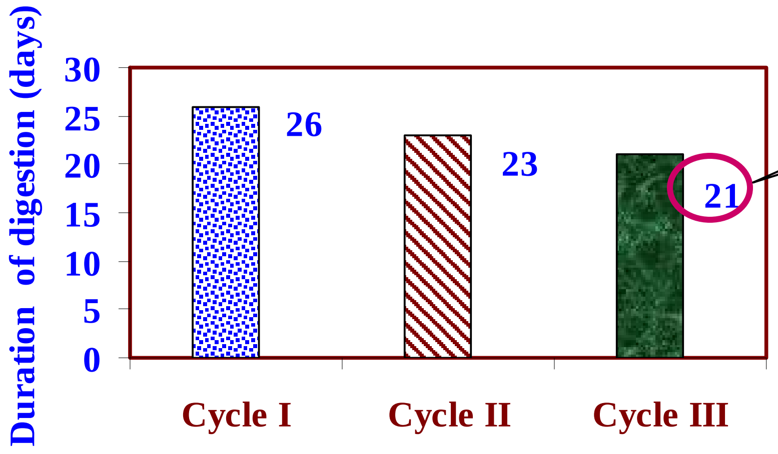
Within flushing Volume used here

Degradation is function of time & cross-circulation rate

Sequential Batch and Continuous Anaerobic Digestion of OFMSW

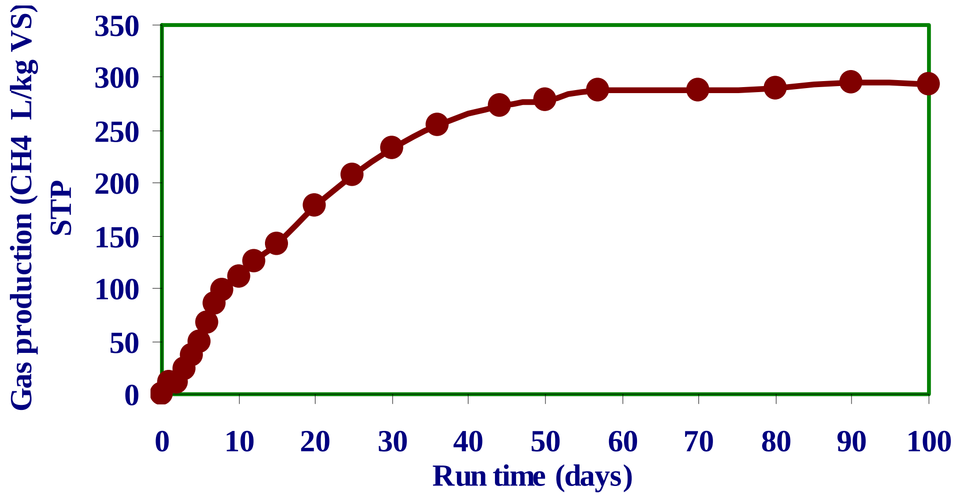






Not only gas yield increased but digestion time also decreased

Page:69



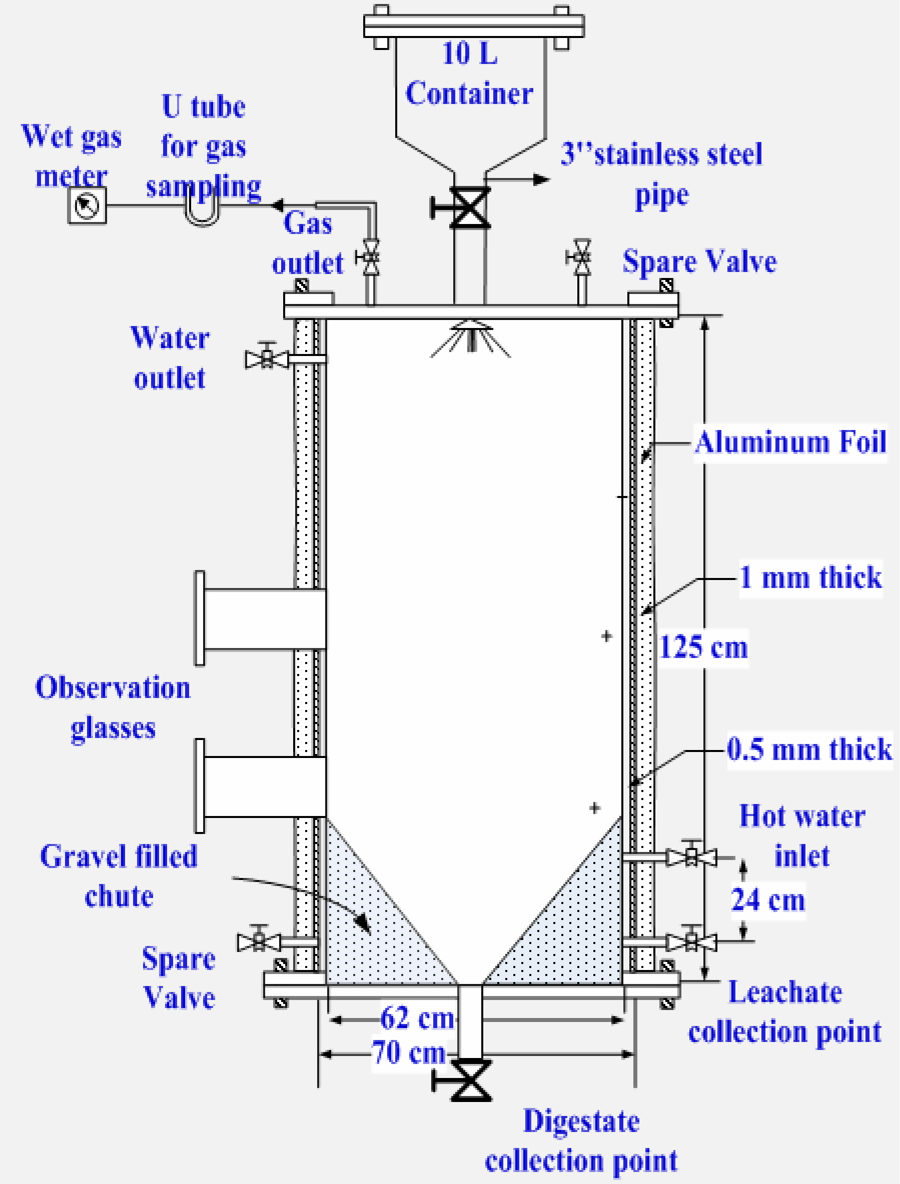
Page:81

BMP→293.8 L/kgVS

Parameters	Units	Run 1	Cycle I	Cycle II	Cycle III
Total vol. biogas	(L)	7225	5927	6669	7262
Duration	Days	76	26	23	21
Total vol. CH_4	(L)	3956	3380	3672	4439
Gas production/kg VS	(L)	275	325	395	418
CH_4/kg VS	(L)	141	185	218	240
Process efficiency	%	49	63	71	82

Page:70

PART II: Continuous Digestion


10 L
Container
Wet gas
meter
U tube
for gas
sampling
3''stainless steel
pipe
Gas
outlet
Spare Valve
Water
outlet
Aluminum Foil
1 mm thick
125 cm
Observation
glasses
0.5 mm thick
Hot water
inlet
24 cm
Gravel filled
chute
Spare
Valve
Leachate
collection point
62 cm
70 cm
Digestate
collection point

Page:40

Feedstock Preparation

Collection: Taklong Dumpsite,
Hand-sorted & shredded to 10mm
Continuous Feeding: Stored at 4°C
thawed before feeding

First Phase Digestion Start up

Feed: 90 kg , intake 50% of volume
Inoculum: 20L (8 kg cow dung, 6 kg sludge, 6 L of water). Acclimatized in 55 °C

19 days

Second Phase Batch Feeding

Feed: 3 kg (1.04 kg VS/m^3/day)
Withdrawal: None

43 days

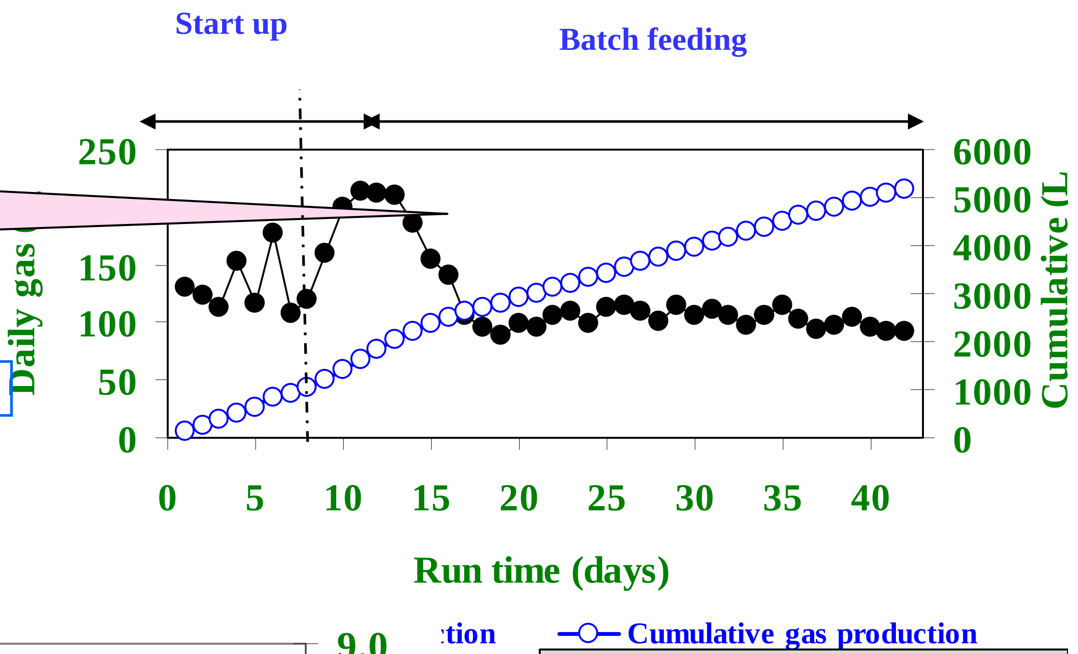
Final Phase Continuous Draw-Fill

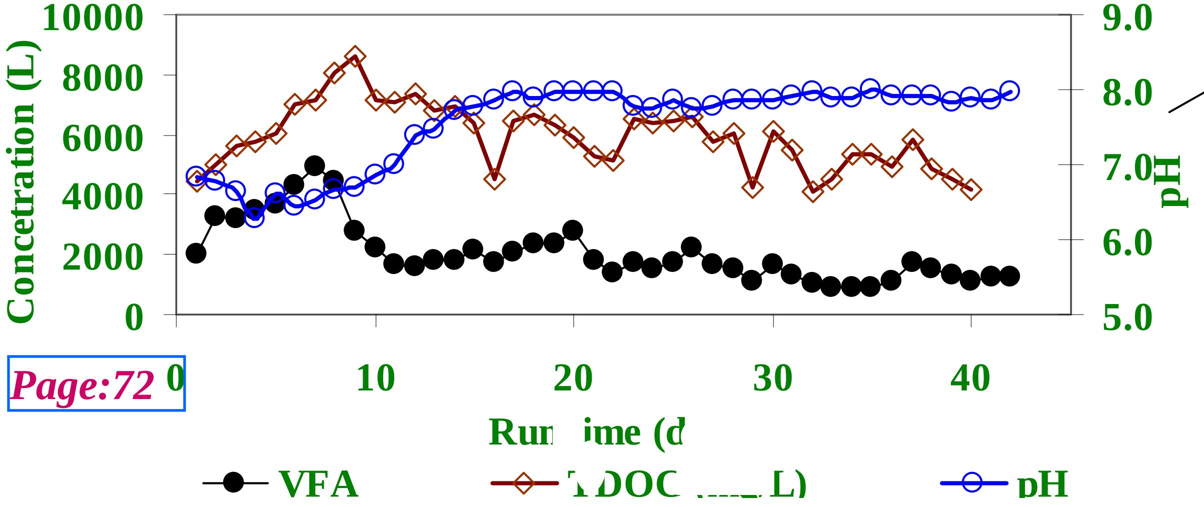
	Kg/d	kgVS/m3.d	MRT (Operation)
Loading 1	5	1.9	32 days (32)
Loading 2	7	2.7	22 days (22)
Loading 3	9	3.5	18 days (18)
Loading 4	11	4.25	12 days (21)

Initial and Startup Phase

Substrate reduction and subsequent Feeding resumption

Page:74

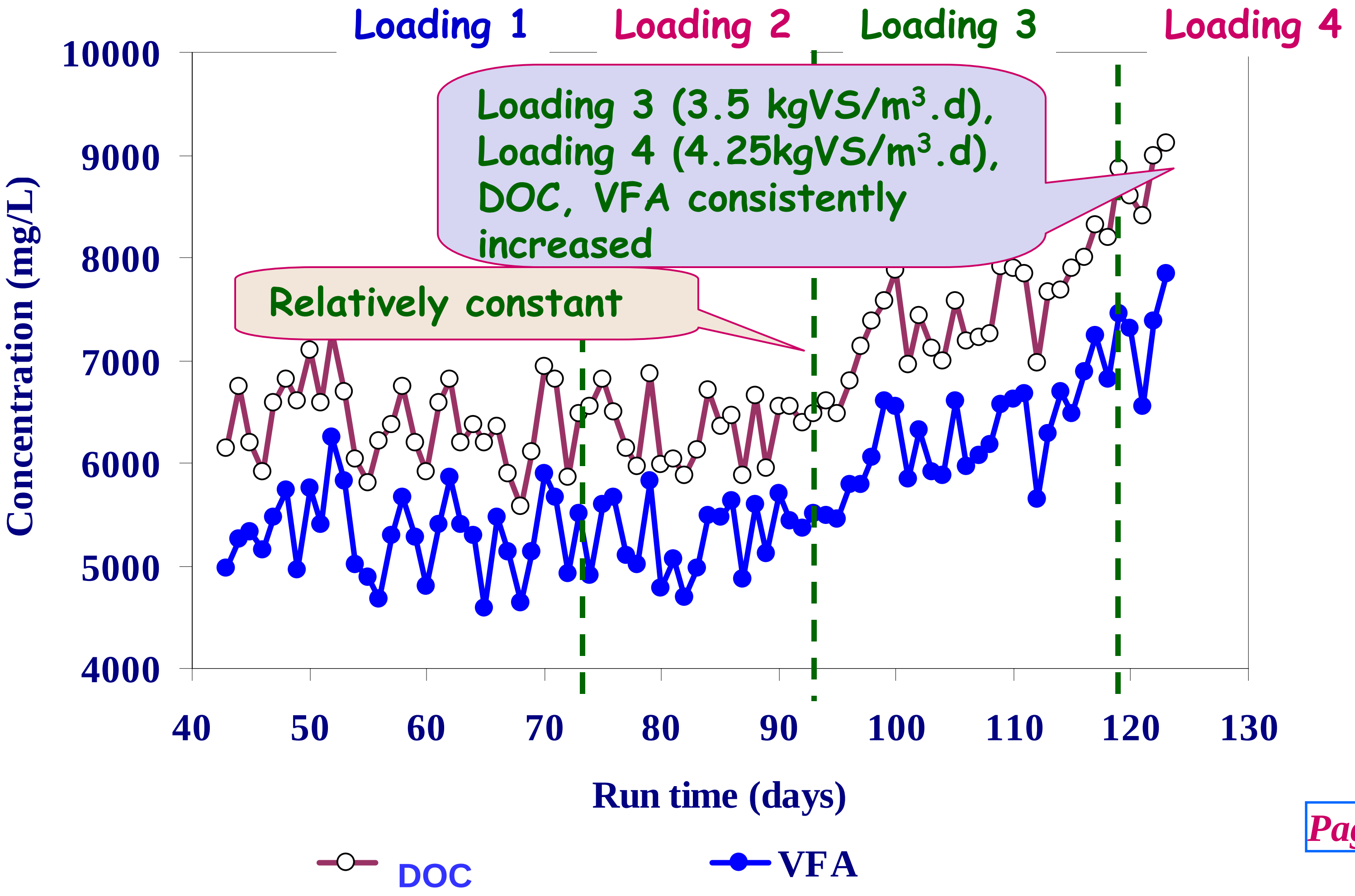




Page:72

pH increased along with reduction in VFA ➔ An Indication of a stable conditions

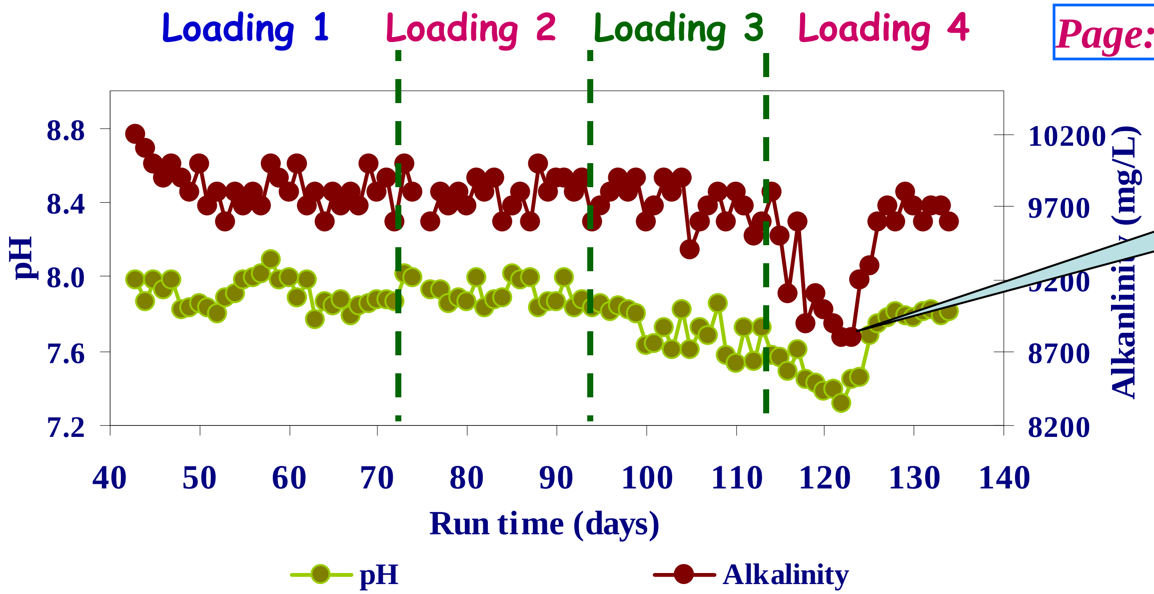
Ms. Radha Adhikari



Loading 3 (3.5 kgVS/m³.d), Loading 4 (4.25kgVS/m³.d), DOC, VFA consistently increased

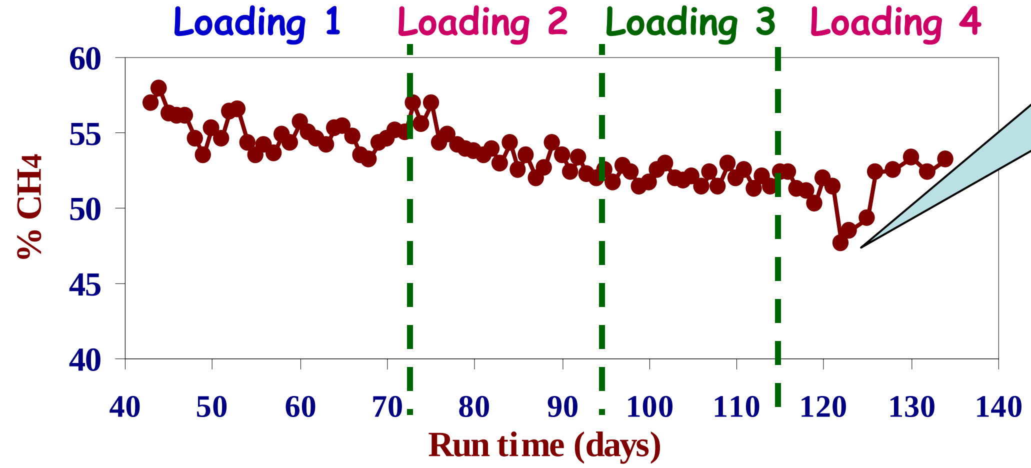
Relatively constant

Page:76



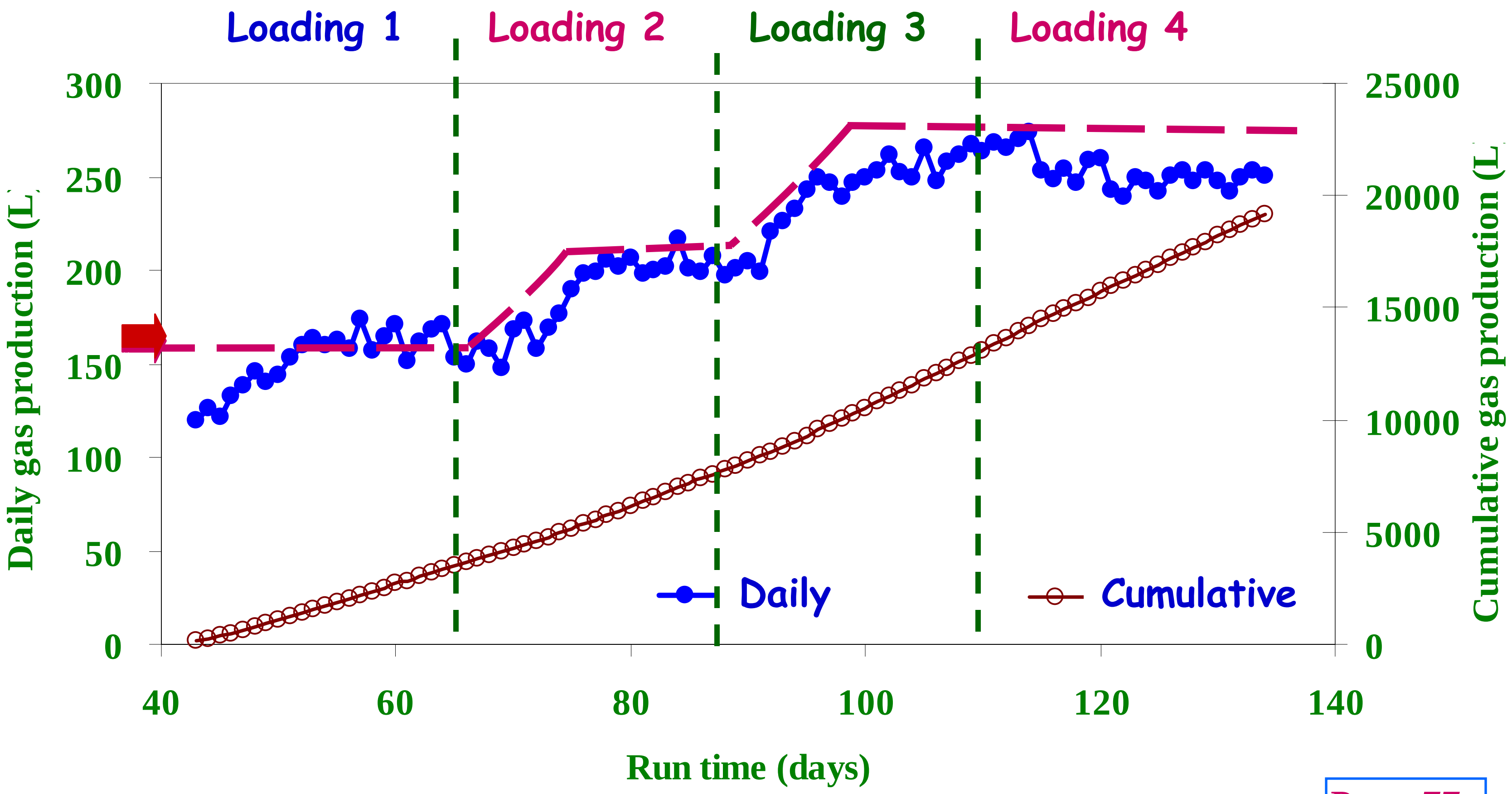
Page:75

Drop in pH



Decrease in methane % in biogas

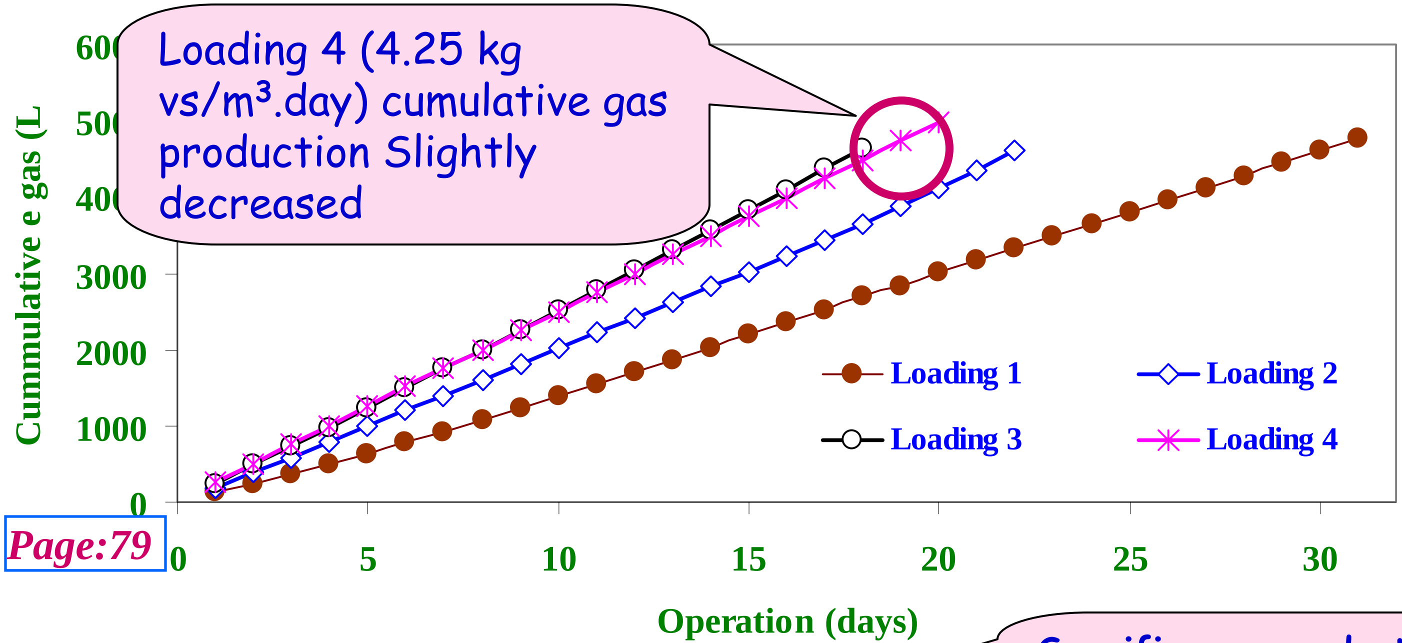
Page:78



Page:77

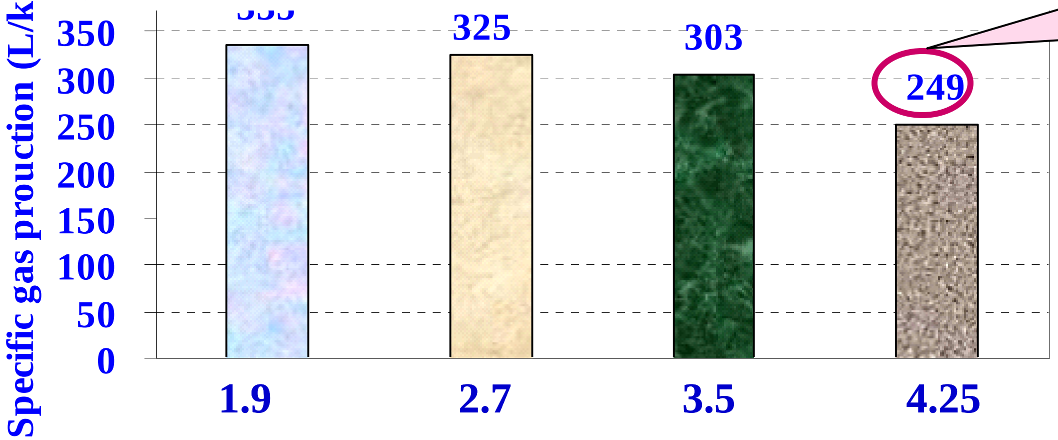
Figure: Daily and Cumulative biogas yield

Sequential Batch and Continuous Anaerobic Digestion of OFMSW



Loading 4 (4.25 kg vs/m³.day) cumulative gas production Slightly decreased

Page:79



Specific gas production decreased significantly at 4.25 kg VS/m³day

Page:80

Ms. Radha Adhikari

Digestate analysis

Nutrients are intact

	Nutrients			TOC (%)	C/N Ratio	Calorific Value (MJ/kg)
	N (%)	P (%)	K (%)			
Thai guideline	1.0	0.8	0.5		<20	
Batch	2.26	0.57	0.6	24.06	10.6	13.81
Continuous	2.17	0.68	0.6	26.66	12.28	14.01

Page:83

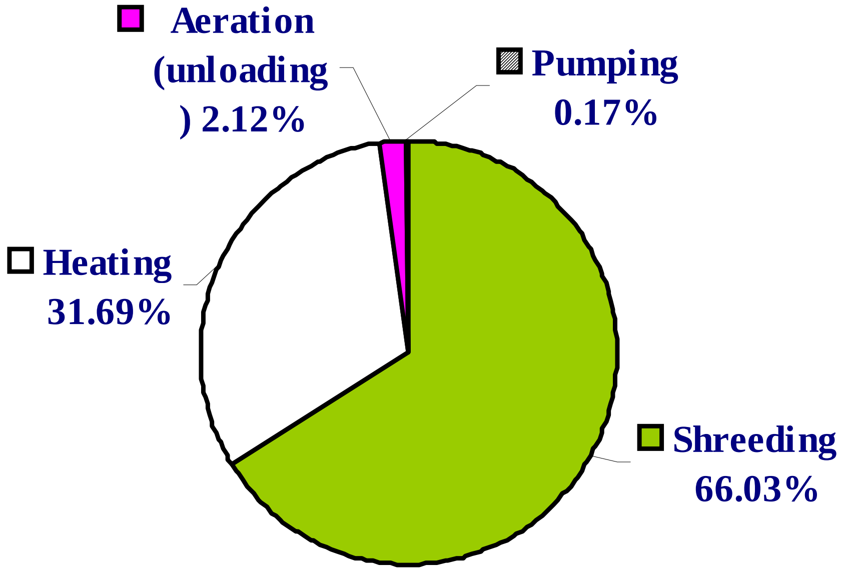
Heavy metal analysis of digestate

Heavy metals within limit

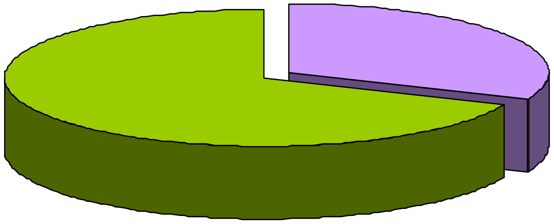
	Heavy metals (mg/kg DM)							
	Cd	Cr	Cu	Pb	Hg	Ni	Zn	Mn
WHO standard	3	50	80	150	1	50	300	-
Batch	0.85	14.5	40	26.2	-	9.75	119	109
Continuous	0.45	5	50	3.2		12.5	55.5	85

Page:82

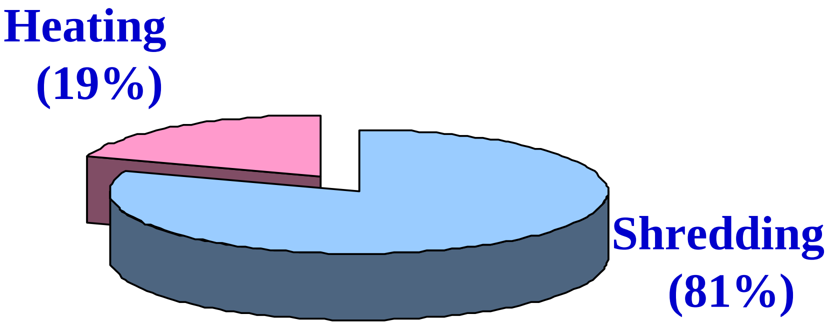
Energy Balance: SEBAC



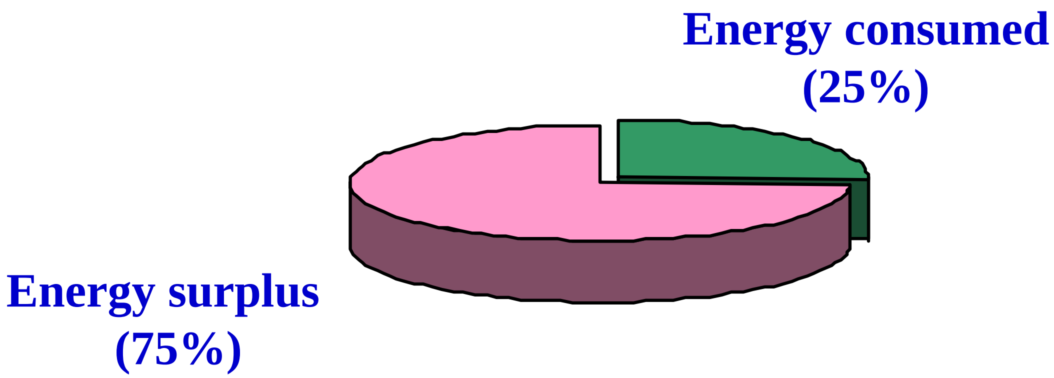
Page:84



Energy Balance: Continuous



Page:85



Conclusions

Part I

Reduced substrate particle size (10 mm) positively influences the efficiency of pre-stage operation

Gradual increment at the rate of 2°C was found satisfactory so long time acclimatization of inoculums does not seem necessary . Gas production higher in thermophilic

Higher cross-circulation resulted into more rapid degradation with shorter digestion time & improved process efficiency (82%)

Higher re-circulation rates not only produce higher biogas but also do so in shorter digestion period

Energy balance in SEBAC showed 66% energy surplus in the system

Conclusions

Part II

A simple continuous reactor that operates on draw-feed mode can be effectively used for AD of OFMSW

The highest biogas production rate of 1.07 L/day per unit waste volume was obtained for the loading rate of 3.5 kg VS/m^3/day

There exists an interesting co-relation between methane concentration in the biogas and biogas production rate

The specific gas production (L/kg.VS) decreases as the loading increases but significantly approach to overloading

Digested quality

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

Alternatively

Digested showed its potential to be used as as RDF (the calorific value~ 14MJ/kg)

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

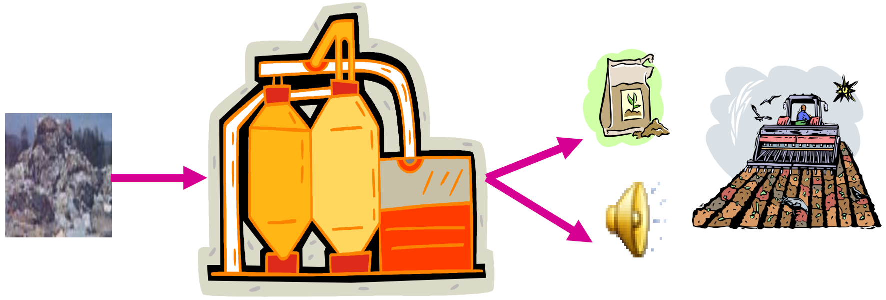
Recommendations

Optimization of sequential staging frequency of cross-circulation

As two-stage gave better results than one stage, modification on continuous digestion configuration

Further investigation of digestate quality

Thank you very much . . . .



Sequential Batch and Continuous Anaerobic Digestion of OFMSW