PERFORMANCE ASSESSMENT AND ENHANCEMENT OF ANAEROBIC DIGESTION OF ORGANIC WASTES FROM A SNACKS PRODUCTION FACILITY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

BEGÜM GÜR ERDOST

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

APRIL 2010

Approval of the thesis:

PERFORMANCE ASSESSMENT AND ENHANCEMENT OF ANAEROBIC DIGESTION OF ORGANIC WASTES FROM A SNACKS PRODUCTION FACILITY

submitted by **BEGÜM GÜR ERDOST** in partial fulfillment of the requirements for the degree of **Master of Science in Environmental Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Gradute School of **Natural and Applied Sciences** ____________

Prof. Dr. Göksel N. Demirer
Head of Department, **Environmental Engineering** ____________

Prof. Dr. Göksel N. Demirer
Supervisor, **Environmental Engineering Department, METU** ____________

Examining Committee Members:

Prof. Dr. Dilek Sanin
Environmental Engineering, METU ____________

Prof. Dr. Göksel N. Demirer
Environmental Engineering, METU ____________

Assoc. Prof. İpek İmamoğlu
Environmental Engineering, METU ____________

Dr. Tuba Hande Ergüder
Environmental Engineering, METU ____________

Emrah Alkaya
Technology Development Foundation of Turkey ____________

Date:

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Begüm, Gür Erdost

Signature :

ABSTRACT

PERFORMANCE ASSESSMENT AND ENHANCEMENT OF ANAEROBIC DIGESTION OF ORGANIC WASTES FROM A SNACKS PRODUCTION FACILITY

Gür Erdost, Begüm

MSc, Department of Environmental Engineering

Supervisor: Prof. Dr. Göksel N. Demirer

April 2010, 111 pages

A snacks company; that manufactures potato, corn and corn grain chips constructed an anaerobic co-digestion facility (ACF) having a total volume of 4200 m^3. The process involved anaerobic co-digestion of anaerobic sludge from its wastewater treatment plant (WWTP), along with organic waste generated in the plant. The anaerobic co-digestion process had two products; 60 % methane containing biogas, and digestate with improved fertilizer characteristics compared to raw organic waste. Produced biogas was being utilized in a co-generation plant, where electricity and heat was produced.

The main objective of this study was to enhance biogas production of the ACF. Two routes were followed for this purpose; first being the investigation of OLR effects in an experimental set-up; and second being the assessment of ACF's biogas production performance through observation of biogas production rate, and OLR. Results obtained from the experiments conducted were used to improve ACF's OLR regime.

Experimenting with Organic Loading Rates of 3.3; 5.3 and 6.4 kg VS/m^3.d; biogas production rates of 114 L/d; 207 L/d and 246 L/d have been obtained respectively. Related biogas yield values have been found out as 0.396; 0.431 and 0.200 L/g VS added.

Based on the results of the experimental study, two conclusions were drawn:

OLR of 5.3 kg VS/m^3.d resulted in the highest biogas production rate, and an OLR of 6.4 kg VS/m^3.d inhibited the mixed anaerobic cultures and thus biogas production capacity.

Regarding the studies realized in real size ACF; adjusting the loading regime and increasing the average OLR from 1.8 kg VS / m^3.d to 3 kg VS / m^3.d resulted an increase of 50% in the biogas production rate; that would result in an annual greenhouse gas saving of 1,534,250 m^3 .

Keywords: Anaerobic Digestion; Organic Loading Rate, Snacks Industry Waste

ÖZ

BİR CİPS ÜRETİM TESİSİNDEN KAYNAKLANAN ORGANİK ATIKLARIN ANAEROBİK ORTAMDA ÇÜRÜTÜLMESİ İŞLEMİNİN PERFORMANS AÇISINDAN DEĞERLENDİRİLMESİ VE İYİLEŞTİRİLMESİ

Gür Erdost, Begüm

MSc, Çevre Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Göksel N. Demirer

Nisan 2010, 111 sayfa

Patates, mısır ve mısır cipsi üretimi yapan bir cips fabrikası; toplam 4200 m^3 lük hacme sahip bir anaerobik kofermantasyon tesisi (ACF) kurmuştur. Bu tesiste gerçekleşen süreç; fabrika arıtma tesisinden (WWTP) kaynaklanan arıtma çamurları ile, fabrikanın organik atıkları anaerobik kofermentantasyonunu içermektedir. Anaerobik kofermantasyon sonucunda iki ürün elde edilir; %60 metan oranına sahip olan biyogaz, ve gübre özelliği ham atığa göre daha yüksek olan organomineral madde. Üretilen biyogaz, kojenerasyon tesisinde değerlendirilmekte ve bunun sonucunda elektrik ile ısı enerjisi elde edilmektedir.

Bu çalışmanın temel amacı; organik atık kofermantasyon tesisinin (ACF) biyogaz üretim kapasitesinin artırılmasıdır. Bu amaçla iki farklı yöntem kullanılmıştır; birincisi, laboratuar ölçekli deneyler yardımıyla OLR etkilerinin araştırılması; ikincisi ise işleyen tesiste (ACF) üretilen biyogaz miktarının teorik miktarla karşılaştırmak; tesis OLR

girdilerini değerlendirmek ve deney sonuçlarıyla karşılaştırmak suretiyle biyogaz üretim performansını değerlendirerek artırılmasını sağlamaktır.

3.3; 5.3 and 6.4 kg VS/m^3.d değerlerindeki OLRler ile yapılan deneylerde sırasıyla; 114 L/d; 207 L/d ve 246 L/d biyogaz üretimi gerçekleşmiştir. Bu değerlere dayanan biyogaz kazanımları ise 0.396; 0.431 and 0.200 L/g VS eklenen olarak gözlenmiştir.

Deney setiyle yapılan çalışmanın sonunda iki sonuca varılmıştır:

En yüksek biyogaz üretim oranının 5,3 kg/ VS/m^3.d değerindeki OLR ile elde edilmiş ve 6,4 kg VS/m^3.d değerindeki OLRnin anaerobik bakteri kültürünü baskıladığı; dolayısıyla biyogaz oluşumunu engellediği saptanmıştır.

.

Gerçek ölçekli tesiste (ACF) yapılan çalışmalar sonucunda ise, besleme rejiminin yeniden düzenlenmesi ve OLRnin 1,8 kg VS / m^3.d'den 3 kg VS / m^3.d' ye çıkarılması sonucunda biyogaz üretiminde %50 artış sağlanmıştır; ve bu artışla yılda 1.534.250 m^3 seragazı salımı tasarrufu sağlanacaktır.

Anahtar Kelimeler: Anaerobik Çürütme; Organik Yükleme Oranı; Cips Endüstrisi

ACKNOWLEDGEMENTS

Thank you...

Prof. Dr. Göksel N. Demirer, for believing in me and the endless encouragement you have provided; it is the faith that moves the world..

Gürdal Erdost, for the tea and hugs; for the sunshine and trust..

Burak, for being such a pure soul that always inspires me to try for the best..

Mom and Dad, for who i am..

Last but not least, my colleagues Erdoğan and Salih, for all the help and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ACF: Anaerobic co-digestion facility

AD: Anaerobic digestion

BOD: Biochemical oxygen demand

C:N ratio: Carbon to nitrogen ratio

COD: Chemical oxygen demand

EU: European Union

F:M : Food to microbe ratio

FVW: Fruit and vegetable waste

HRT: Hydraulic retention time

MCRT: Mean cell residence time

MFC: Microbial fuel cell

MSW: Municipal solid waste

OLR: Organic loading rate

PC: Potato Chips production line

TC: Tortilla (corn) Chips production line

SRT: Solids retention time

TKN: Total Kjehldahl Nitrogen

TS: Total Solids

UASB: Upflow Anaerobic Sludge Blanket

VFA: Volatile fatty acids

VS: Volatile Solids

VSS: Volatile Suspended Solids

WAS: Waste activated sludge

WWTP: Wastewater treatment plant

CHAPTER 1

INTRODUCTION

1.1. Background Information

In an era where natural sources are continuously being exploited and becoming scarce; industrial pollution is spreading like an epidemic; consequences of climate change is threatening all kinds of living organisms; and relying on fossil fuels for energy production is no more an option; immediate sound measures should be taken for creating "sustainable businesses". Traditional environmental mottos like "reuse, reduce, recycle" are still of value; however nature calls for smarter approaches. Options for "doing more with less" should be investigated; i.e, for sustaining the business and environment at the same time.

As is stated in the Renewable Energy Road Map communication of European Union Commission (2006) and in United States National Research Council (1995); shifting to high-tech industries, and using renewables as the energy source are the only options for making this happen :

> *"The EU and the world are at a cross-roads concerning the future of energy. In the complex picture of energy policy, the renewable energy sector is the one energy sector which stands out in terms of ability to reduce greenhouse gas emissions and pollution, exploit local and decentralised energy sources, and stimulate world-class high-tech industries."*

"We are convinced that socially compatible and environmentally sound economic development is possible only by charting a course that makes full use of environmentally advantegeous technologies. By this, we mean technologies that utilize resources as efficiently as possible and minimize environmental harm while increasing industrial productivity and improving quality of life".

The most cost effective and sustainable approach for using renewables that will ease the stress on depleting natural resources and growing energy insecurity is to employ a biotechnology option in industries (Khanal, 2008)

Anaerobic biotechnology can be used for utilizing waste resulting from industrial applications; yielding to useful byproducts and renewable biofuels. Agricultural industries (Gavala et al., 1996) and food industries (Ferreira das Neves, 2009; Carucci et al., 2005; Parawira, 2004) are ideal candidates for anaerobic biotechnology applications.

The anaerobic digestion process is regarded as one of the best methods that can be used to utilize residues from livestock farming, food processing industries, wastewater treatment plant sludge among other organic wastes, to yield digestate and biogas (Environmental Protection Agency of Ireland, 2005). Carbon, nitrogen, hydrogen and sulphur from municipal, agricultural and industrial solid and liquid wastes are converted into value-added resources. These include biofuels (hydrogen, butanol and methane); electricity from microbial fuel cells (MFCs), fertilizers (biosolids), and useful biochemicals (organic acids, alcohols, etc.) (Khanal, 2008).

Snacks industry generates high amounts of organic waste and high strength wastewater. Effective handling of organic waste resulting from snacks production industry is of utmost importance; since this highly biodegradable waste can create environmental and public health effects such as oxygen depletion, odor, nutrient enrichment and insect problems. Meanwhile organic waste from this industry actually is a valuable by-product that can be used in bio-energy and fertilizer production.

High organic content and high-strength COD and BOD levels present in the effluents, make this industry's waste ideal for conversion to biofuels as Custodio et al. (2006) advocated.

Anaerobic digestion process has been proven to improve the fertilizer quality of the wastewater treatment plant sludge (WWTP sludge), and to utilize the calorific energy potential in the organic waste produced by means of potato and corn snacks production processes. The process involves anaerobic co-digestion of WWTP sludge, together with organic waste produced in the plant. The anaerobic digestion process has two products. One is biogas which is approximately 60 % methane and has a high calorific value; the other is the digestate which has improved fertilizer characteristics compared to raw organic waste. Produced biogas is utilized in a co-generation plant, where electricity and heat is produced.

However, literature review has proven that the biogas production capacity of such facilities can be manipulated through various means, such as switching from conventional one-phase operation to two-phase operation, or manipulation of operational parameters such as organic loading rates (OLR), hydraulic retention times (HRT), mean cell residence time (MCRT), temperature and pH (Gunaseelan, 1995; Ward et al., 2008; Callaghan et al., 2002; Parawira et al., 2008).

1.1. GOAL AND SCOPE

Literature provides studies on anaerobic digestion of potato processing waste (Kaparaju and Rintala, 2005; Zhu et al., 2009), potato processing wastewater (Catarino et al., 2007; Hadjivassilis et al., 1997; Senturk et al., 2009), food and beverage waste (Babel et al., 2009; British Biogen, 1997; Carucci et al., 2005; Darlington et al., 2009; Das Neves, 2009; Murto et al., 2004; Wang et al., 1997), Fruit and vegetable waste (FVW) (Alvarez and Lidén, 2008; Bouallagui et al., 2003, 2004, 2005, 2009; Callaghan et al., 1999, 2002; Custodio et al., 2006; Ward et al., 2008), however co-digestion of snacks industries' wastewater with the organic waste produced during the process has not been investigated so far.

Despite the fact that organic waste from this industry being a valueable by-product that can be used in bio-energy and fertilizer production; and considering environmental and public health effects problems such as oxygen depletion, odor, nutrient enrichment and insects that might arise from inefficient handling of those, there is a gap in the literature for pointing out ways to handle these two waste streams in an integrated manner.

A snacks company, which is mentioned as "Plant" throughout this study; that manufactures potato, corn and corn grain chips constructed an anaerobic co-digestion facility (ACF) consisting of two reactors, having 1200 m^3 and 3000 m^3 in volume, respectively. Since the facility is of the firsts in its kind, and literature does not have supporting data on the subject matter; it needs further research to be operated effectively. Ward et al. (2008) also stated that, commercial anaerobic digestion processes were often operated well below their optimal performance due to a variety of factors, although the production of biogas through anaerobic digestion was not a new idea.

In order to investigate optimal conditions for the ACF, an experimental set-up was constructed, that was modelled from the real-size ACF. Organics Loading Rate (OLR) was chosen as the operational paramater to be tested on the experimental set – up, based on the works conducted by Batstone et al., (2002); Bouallagui et al., (2005); Cecchi et al., (1986); Murto et al., (2004) regarding the subject. Three different OLRs were investigated, through experiments conducted with the experimental set-up.

Moreover, ACF was introduced regarding to its design, operating principles and biogas generation. Biogas production performance of this facility is assessed through observation of actual monthly biogas production rate, biogas methane content; and operational parameters such as organic waste admission and OLR. Greenhouse effects are determined by setting out the energy produced by utilization of biogas in the ACF, and corresponding decrease in greenhouse gas emissions.

To summarize, the main objectives of this study were defined as:

- Assessment of biogas production performance of the ACF;
- Investigation of ACF's biogas production rate enhancement opportunity via increasing the OLR, that was tested with the experimental set-up; and,
- Estimation of reduction in greenhouse effects via evaluating the net energy produced in the ACF with the utilization of generated biogas.

Investigation of OLR effects for biogas production rate enhancement was conducted via laboratory studies using an experimental set-up for three different OLRs.

CHAPTER 2

LITERATURE REVIEW

2.1 Anaerobic Digestion

2.1.1 History and definitions

Anaerobic digestion is the process of decomposition of organic matter by a microbial consortium in an oxygen-free environment (Pain and Hepherd, 1985). It is a process found in many naturally occurring anoxic environments including watercourses, sediments, waterlogged soils and the mammalian gut. It can also be applied to a wide range of feedstocks including, agricultural (Parawira, 2004; Gavala et al.,1996; Kaparaju et al., 2005), municipal (Stroot et al.,2001; Gomez et al. 2006; Sosnowski et al., 2003) , food industry wastes (Ferreira das Neves, 2009; Carucci et al.,2005; Alkaya, 2008), fruit and vegetable wastes (Bouallagui et al., 2005), animal manure (Yılmaz and Demirer 2008; Demirer and Chen, 2004) and plant residues (Mata-Alvarez et al., 2000).

The production of biogas through anaerobic digestion offers significant advantages over other forms of waste treatment, including:

- Displacement of greenhouse gases from fossil fuels, thus resulting in lower greenhouse gas emissions (EPA, 2005).
- Production of less biomass sludge (IEA Bioenergy, 2001)
- Successful treatment of wet wastes of less than 40% dry matter (Mata-Alvarez, 2002).
- Minimal odour emissions as 99% of volatile compounds are oxidatively decomposed upon combustion, e.g. H_2S forms SO_2 (Smet et al., 1999).

- Improvement of produced slurry's (digestate) fertiliser characteristics, in terms of both its availability to plants (Tafdrup, 1995) and its rheology (Pain and Hepherd, 1985).

The science of anaerobic digestion is as old as scientific research can be, and, includes the names of world's most famous researchers. The application of biotechnology dates back to at least the tenth century, when the Assyrians used it for heating bath water (Khanal, 2008). Benjamin Franklin described as early as 1764 that biogas was able to light a large surface of a shallow muddy lake, in New Jersey. This experiment was reported in a letter to Joseph Priestly in England, who published his own experiences with the inflammable air in 1790 (Titjen, 1975). Alexander Volta recognized that the anaerobic process resulted in conversion of organic matter to methane gas (McCarty, 2001).

Even so, it was only at the end of the 19th century that anaerobic digestion was applied for the treatment of wastewater and solid waste (Gijzen, 2002). The first application of anaerobic digestion for sewage treatment dates back to 1860, with the development of a simple air tight chamber by Mouras in France.Patented in 1881; the system had been installed in 1860 (Mc Carty, 2001). A "septic tank" , modeled on the Mouras Automatic Scavenger was approved in Exeter, England; for the treatment of the entire wastewater of the city in 1897. With the development of a two-stage system known as the Travis tank (1905) and the Imhoff tank (1905), the focus shifted from wastewater treatment to settled sludge treatment.Separate sludge digestion was reported at Essen-Rellinghausen, Germany that enabled the public to recognize importance of power generation from methane (Khanal, 2008)

Although anaerobic wastewater treatment has been used since the late 19th century, it was for a long time considered to be unstable, inefficient and a slow process (Gijzen, 2002). The major limitation in the development of high rate anaerobic digesters was the low yield and long doubling times of the microorganisms, especially for those involved in the acetogenic and methanogenic reactions (Gijzen, 2002). Stander was the first to recognize the importance of Sludge Retention Time (SRT) for successful treatment of different wastewaters; and this has been the basis for development of high-rate anaerobic reactors. Some of the widely used high-rate anaerobic reactors are Upflow Anaerobic Sludge Blanket (UASB) reactor, expanded granular sludge bed, anaerobic filter, fluidized bed, and hybrid systems (Khanal, 2008)

It was only at the beginning of the new century that anaerobic digestion returned, once more, to the market for its energy recovery potential, with applications to various bio-wastes and biomass. Actually, now in China, about 25 million people use biogas for cooking and lighting for 8-10 months a year (Babel et al., 2009).

Biogas production attained by anaerobic digestion of organic wastes has been carried out for decades, and, it is in many cases a mature concept. However, it is still capable of showing new features, as Mata-Alvarez et al. (2000) declared that only 30% of the industrial biogas potential is being produced in Europe.

2.1.2 Process Description

The anaerobic digestion process can be divided in four main steps. First step is the hydrolysis of the input material, where insoluble and soluble organic polymers are broken down in their monomers, making them available for the subsequent steps. Second step is the acidogenesis, also known as fermentation: This step involves the conversion of sugars, amino acids and long chain fatty acids into CO_2, Hydrogen, Ammonia, Alcohols and Organic acids. Followed by acidogenesis is the acetogenesis, where the intermediates such as alcohols and organic acids are converted into acetic acid, H_2, and CO_2. Methanogenesis is the last step where all the products are converted to CH_4 and CO_2 (Ferreira das Neves, 2009). Slow-growing methanogenic microorganisms are obligate anaerobes and are sensitive to changes in environmental and operational conditions which make this stage “rate-limiting” in most of the cases.Overall reaction is provided in Figure 2.1.

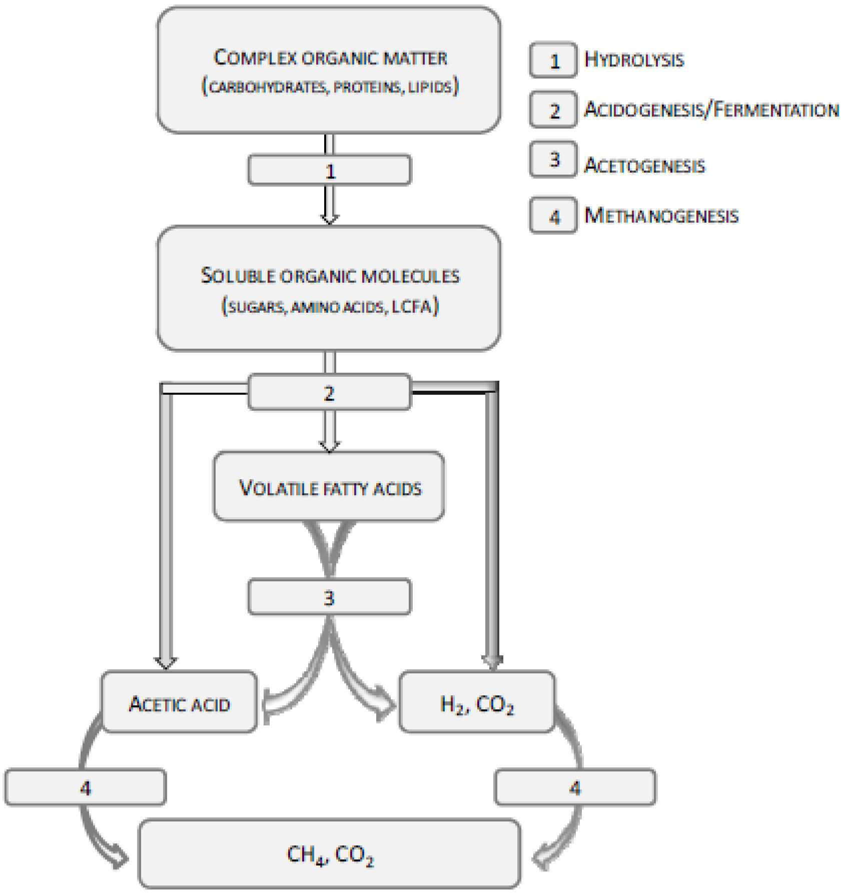

Figure 2.1 Anaerobic digestion process (Ferreira das Neves, 2009)

2.1.3 Factors affecting anaerobic digestion

It is in the interest of researchers to maximise methane production while concomitantly reducing the chemical oxygen demand of the digested material. Although the production of biogas through anaerobic digestion is not a new idea, commercial anaerobic digestion processes are often operated at well below their optimal performance due to a variety of factors (Ward et al., 2008).

Biogas is a product of anaerobic degradation of organic substrates, which is one of the oldest processes used for the treatment of industrial wastes and stabilization of sludges. Since it is carried out by a number of microorganisms; it depends on various factors like pH, temperature, HRT, and C/N ratio.

Different methods used to enhance biogas production can be classified into the following categories:

- Use of additives,
- Recycling of slurry and slurry filtrate,
- Variation in operational parameters like pH, Organic Loading Rate and temperature,
- Hydraulic retention time (HRT) and particle size of the substrate,
- Use of fixed film/biofilters,
- Co-digestion,
- Phase separation,
- Novel reactor configurations,
- Pretreatment.

Some of the important parameters will be summarized below:

Operational Parameters

The operational and environmental parameters of the process obviously affect the behaviour, performance and eventually the fate of the microbial community in anaerobic digesters. The most influential parameters can be listed as: organic loading rate (OLR), solids retention time (SRT), buffering capacity (alkalinity) and pH, temperature, and nutrients (Murto et al., 2004; .Ward et al., 2008; Bouallagui et al., 2009; Torres and Lloréns, 2008)

Temperature

There are three common temperature ranges for anaerobic digestion:
(1) the lower temperature range, which is referred to as psychrophilic, meant for temperatures lower than 20ºC;
(2) temperatures within 20–45ºC, named mesophilic temperatures;
(3) temperatures in the range of 45–60ºC, are termed thermophilic temperatures.

Nonetheless, most of the reactors operate at either mesophilic or thermophilic temperatures, with optima at 35ºC and 55ºC, respectively (Bouallagui, 2003; Ward et al., 2008).

Temperature affects the metabolic activities of the microorganisms that, in turn, affect the rate of digestion and CH_4 production (Ward et al., 2008). Even small changes in temperature, from 35ºC to 30ºC and from 30ºC to 32ºC reduce biogas production rate (Chae et al., 2008).

There is not a standard or optimal temperature range for the anaerobic digestion, since there are studies for mesophilic and thermophilic conditions with conflicting results (Parawira et al., 2008; Kim et al., 2003).

Buffering capacity and pH

There are two groups of bacteria in terms of pH optima, namely acid-producing bacteria (acidogens) and methane producing bacteria (methanogens). The acidogens prefer a pH of 5.5-6.5; while methanogens prefer a range of 7.8-8.2. In an environment where both cultures coexist, the optimum pH range is 6.8-7.4. Since methanogenesis is considered as the rate limiting step; where both groups of bacteria are present, it is therefore neceassary to maintain the reactor pH close to neutral. (Khanal, 2008).

Buffer capacity is often referred to as alkalinity, which is the equilibrium of CO_2 and bicarbonate ions that provides resistance to significant and rapid changes in acid /

alkali concentrations. The buffering capacity is, therefore, proportional to the concentration of bicarbonate (Ward et al.,2008). Increasing a low buffer capacity is best accomplished by reducing the organic loading rate. A more rapid approach is the addition of strong bases or carbonate salts to remove CO_2 from the gas space and convert it to bicarbonate, or alternatively bicarbonate can be added directly. Direct bicarbonate addition is more accurate, as converting CO_2 to bicarbonate will require a time lag for gas equilibrium to occur which could result in over dosing (Ward et al., 2008).

The desired operating pH in the reactor can be achieved either by adjusting the pH of the influent feed, or by controlling the pH in the reactor per se. (Khanal, 2008)

Organics Loading Rate

The OLR is the quantity of organic matter fed per unit volume of the digester per unit time, (e.g., kg VS/m^3.d). OLR plays an important role in anaerobic wastewater treatment in continuous systems and is a useful criterion for assessing performance of the reactors (Rajeshwari et al., 2000). High OLRs and low sludge production are among the many advantages of anaerobic processes over other biological processes (Batstone et al., 2002).

There is a long tradition of treating sewage sludge anaerobically at wastewater treatment plants to reduce the volume of sludge, but the process has not been focused on optimal biogas production. Anaerobic digesters are often very simple in construction and the process is poorly monitored. As a result, they are often run at a low OLR to avoid overload. In the European Union society where landfilling of organic waste is prohibited or limited it would be of interest to use the already existing biogas plants for waste treatment (Murto et al., 2004).

The CSTR is normally operated at an HRT of 20-30 days and a loading rate of 1.7 kg VS/m^3.d (Parawira, 2004) It permits the conversion of 70–95% of organic matter to methane, with a volumetric organic loading rate (OLR) of 1–6.8 g volatile solids VS/L. d (Bouallagui et al., 2005)

Mata-Alvarez et al. (1992) examined the performance of the mesophilic one-stage completely stirred reactor for the treatment of the organic fraction of the wastes coming from a large food market. The maximum organic loading rate (OLR) tested was below 3 kg VS/m^3.d. The OLR of 6 kg VS/ m^3.d was found to be a limit condition for a similar waste digestion (Cecchi et al., 1986)

Overloading of digesters with FVW above 4 kg VS/m^3.d was also reported by Lane et al. (1979) to resu in a fall in pH and gas yield and an increase in the CO_2 content of gas produced using a continuously stirred tank reactor (Lane et al., 1979)

In the case of feeding exclusively source-sorted OFMSW, or fruit and vegetable wastes, or, in general, highly biodegradable wastes, it is advisable to use a two-phase anaerobic digestion process, which permits much higher loads in the digester (Mata-Alvarez et al.; 2000).

Hydraulic Loading Rate (HRT)

HRT is the average time spent by the input slurry inside the digester before it comes out. It is one of the most important design parameters influencing the economics of digestion. For a given flow of wastewater, a shorter HRT means that the volume of digester will be small; and a longer HRT means the contrary. (Parawira, 2004). For a digester with no sludge recycling; the HRT will be equal to SRT (Metcalf and Eddy, 2003)

Pre-Treatment

Not all substrates are easily hydrolysed. To overcome this limitation, several authors denote the need of a pretreatment, in order to increase substrate bioavailability by the anaerobic consortium. A review of pretreatments to enhance the digestibility of lignocellulosic biomass was recently published by Hendriks and Zeeman (2009). Pretreatment of wastes can increase biogas production, VS reduction and yield in increased solubilisation.

2.1.4 Anaerobic co-digestion of wastes

Co-digestion is the simultaneous anaerobic decomposition of mixture of two or more organic substrates (Sosnowski et al., 2008). The basic principle of co-digestion consists in balancing several parameters in a selected substrate mixture. Such a balance involves qualitative and quantitative characteristics of waste originating from different sources. The quantitative character of individual component indirectly influences the quality of the mixture (Montusiewicz et al., 2008).

Several researchers have studied the anaerobic co-digestion of sewage sludge with the organic fraction of municipal solid waste (OFMSW) or with agricultural wastes and stated that an enhancement in CH_4 yield was achieved (Angelidaki and Ellegaard, 2003; Bolzonella et al.,2006; Gomez et al., 2006; Pavan et al., 2007; Romano and Zhang, 2008).

Therefore, anaerobic co-digestion of biowaste and sludge can be considered a sustainable solution for wastewater treatment plants, where several different kinds of biowaste are available to enhance biogas production (Pavan et al., 2007). Apart from higher biogas yields due to positive synergetic effects on microorganisms (Cecchi et al., 1996; Mata Alvarez et al., 2000), there are other benefits of co-digestion approach, which are:

- Dilution of toxic substances coming from any of the substrates involved (Cecchi et al., 1996; Murto et al., 2004), including, possible removal of some xenobiotics (detoxification based on cometabolism process) (Cecchi et al., 1996);
- Improving nutrient balance (Cecchi et al., 1996, Murto et al., 2004);
- Reducing micro and macronutrient deficiency (Montusiewicz et al., 2008);
- Improving process stability (Montusiewicz et al., 2008);
- Establishment of required moisture contents of the digester feed, with the use of a cosubstrate (Sosnowski et al., 2003).

- Better handling and digestibility achieved by mixing solid waste with diluted waste (Murto et al., 2004); and
- Economic advantages retained by sharing equipment with WWTP(Mata Alvarez et al., 2000).

The major biotechnical advantage of the co-digestion of agro-residues and co-substrates is overcoming the problem in the digestion of agro-residues alone of maintaining a stable pH within the methanogenesis range (Brummeler and Koster, 1990).

There are many examples of success from mixing organic wastes in anaerobic digestion. Codigestion of cattle manure slurry with fruit, vegetable wastes and chicken manures is a good example of success. Callaghan et al. (2002) blended high carbon-to-nitrogen (C/N) ratio and low C/N feedstock and improved digester performance. Additionally, Bolzonella et al. (2006) presented the results of two full scale applications of the anaerobic co-digestion process of waste activated sludge together with the OFMSW The experiences were carried out at Viareggio and Treviso wastewater treatment plants, in Italy. In the first plant, 3 tons/d of source sorted OFMSW were co-digested with waste activated sludge, increasing 50% the biogas production. At the Treviso plant, 10 tons/d of separately collected OFMSW were treated using a low energy consumption sorting line, in which 99% and 90% of metals and plastics respectively were removed. In these conditions, the biogas production increased from 3500 up to 17500 m^3/month.

A particularly strong reason for co-digestion of feedstocks is the adjustment of the carbon-to-nitrogen (C:N) ratio. Microorganisms generally utilise carbon and nitrogen in the ratio of 25–30:1, but C:N ratios can often be considerably lower than this ideal, for example sewage sludge has a C:N ratio of approximately 9:1 (Kizilkaya and Bayrakli, 2005). Feedstocks can vary widely in their C:N ratios, and some reactors are affected more than others by nonideal ratios. Indeed, the two-stage reactor with biomass retention has been reported to be considered the only type capable of reliable activity with C:N ratios less than 20 (Mata-Alvarez, 2002). Co-digestion of a low C:N ratio feedstock with a high C:N ratio feedstock such as biomass can adjust the ratio closer to ideality (Ward et al., 2008). Main substrate sources for co-digestion can be found in Figure 2.2. (Weiland, 2000).

Despite the positive results obtained in the studies; the scarce industrial application of co-digestion is surprising (Mata-Alvarez et al., 2000). Food processing residues currently exist in large quantities and should be seen as resources which, among other things, provide an opportunity to develop the AD industry. It is estimated that, every year, in excess of one million tons of food production residues (such as vegetable residues) are generated, that could be suitable for AD. (British Biogen, 1997).

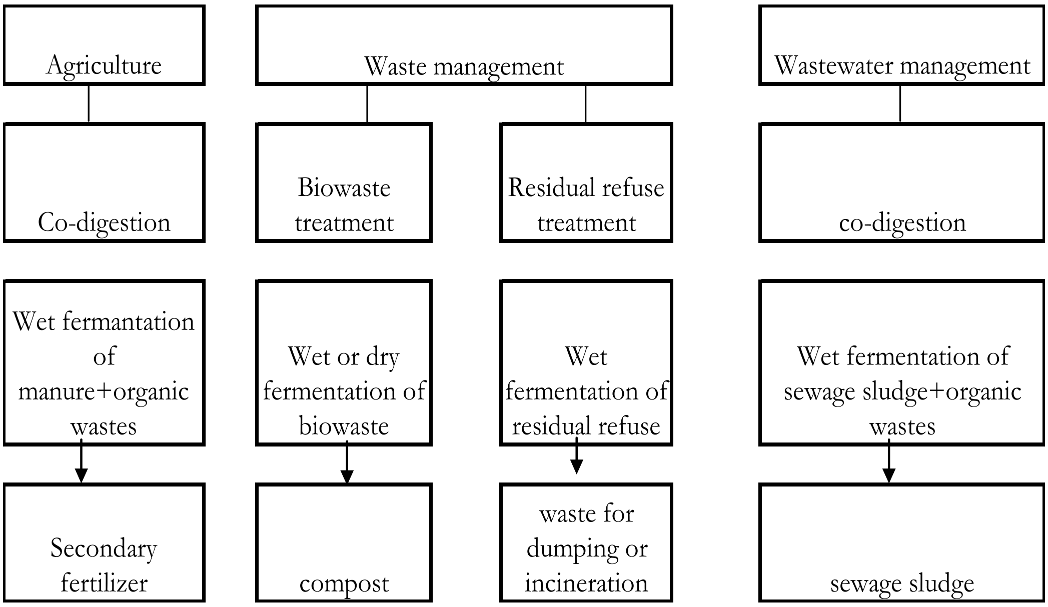

Figure 2.2. Application of anaerobic solids treatment (Weiland, 2000)

2.1.5 Vegetable waste and anaerobic digestion

Vegetable wastes tend to have low total solids and high volatile solids, and are easily degraded by anaerobic digestion process (Gunaseelan, 1997; Ward et al., 2008 ; Weiland, 2000) Methane yields from different types of fruit and vegetable biomass can be found in Table 2.1.

The easy biodegradable organic matter content (around 75%) of food and vegetable waste (FVW) with high moisture facilitates their biological treatment and shows the trend of these wastes for anaerobic digestion. In general, hydrolysis is the rate limiting step if the substrate is in particulate form. However, the anaerobic degradation of cellulose-poor wastes like FVW is limited by methanogenesis rather than by the hydrolysis. A major limitation of anaerobic digestion of FVW is a rapid acidification of these wastes decreasing the pH in the reactor, and a larger volatile fatty acids production, which stress and inhibit the activity of methanogenic bacteria (Bouallagui et al., 2005). The rapid hydrolysis of these feedstocks may lead to acidification of a digester and the consequent inhibition of methanogenesis (Ward et al., 2008). One of the most important tests to judge the acidification rate of the digester is the determination of VFAs in the effluent. VFAs are short chain fatty acids and are the intermediated formed during anaerobic fermentation of complex organic materials. For a normal operating anaerobic system, the effluent VFA concentration ranges from 50 to 250 mg/L as acetic acid (Sawyer et al., 2003).

It was discovered in the late 1970s and early 1980s that many carbohydrate-rich feedstocks were found to require either co-digestion with other feedstocks or addition of alkaline buffer to ensure stable performance (Hills and Roberts, 1982; Knol et al., 1978). Two-stage reactors effectively use the first stage as a buffer against the high organic loading rate which offers some protection to the methanogens. Separation of the acidification process from methanogenesis by the use of sequencing batch reactors has been shown to give higher stability, a significant increase in biogas production and an improvement in the effluent quality when used with fruit and vegetable waste (Bouallagui et al., 2004).

The biomethanation of FVW is accomplished by a series of biochemical transformations, which can be roughly separated into four metabolic stages which can be found in Figure 2.3 (Bouallagui et al., 2005). First, particulate organic materials of FVW like cellulose, hemicellulose, pectin, and lignin, must undergo liquefaction by extracellular enzymes before being taken up by acidogenic bacteria. The rate of hydrolysis is a function of factors, such as pH, temperature, composition, and particle size of the substrate and high concentrations of intermediate products. After that,

soluble organic components including the products of hydrolysis are converted into organic acids, alcohols, hydrogen, and carbon dioxide by acidogens. The products of the acidogenesis are then converted into acetic acid, hydrogen, and carbon dioxide.

Finally, methane is produced by methanogenic bacteria from acetic acid, hydrogen, and carbon dioxide as well as directly from other substrates of which formic acid and methanol are the most important (Bouallagui et al., 2009).

Yields from the biomethanization process are very much dependent on the particular situation of each plant. Of course the main factor affecting this yield is the kind of substrate used (Mata-Alvarez et al., 2000) For example, the presence of FVW and chicken manure gave a reduced yield in the batch studies performed by Callaghan et al (1999), for co-digestion of waste organic solids.

Table 2.1 Ultimate methane yields of fruit and vegetable wastes (Gunaseelan, 1997)

Type of Fruit/Vegetable Biomass	**CH_4 Yield (m^3/kg VS added)**
Banana (fruit and stem)	0.529
Fruit and vegetable waste mixture	0.510
Ipomoea leaves	0.429
Potato waste	0.426
Cauliflower leaves	0.423
Tomato processing waste	0.420
Carrot waste	0.417
Banana peeling	0.409

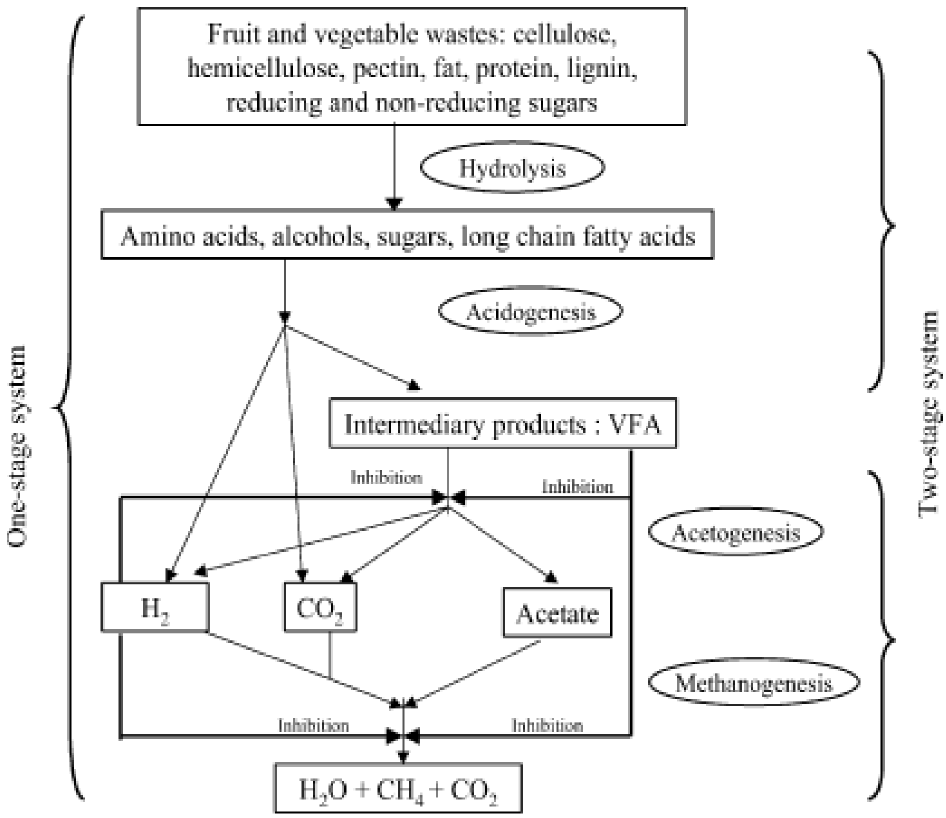

Fig. 2.3 Reactions scheme for anaerobic digestion of particulate organic material of FVW (Bouallagui et al., 2005)

Bouallaqui et al. (2004) studied bioreactor performances for digesting FVW at different organic loading rates, and the resulting biogas yields have been found to be 0.36; 0.45 and 0.45 for OLRs of 0.72; 1.29 and 1.65 g COD/L. d respectively.

Dinsdale et al. (2000) studied the two-stage anaerobic co-digestion of WAS and FVW using inclined tubular digesters and found the biogas yield to be 0.37 m^3/kg VS added at an OLR of 5.7 kg VS / m^3.d

Kaparaju et al. (2005) stated that the methane yields (m^3 /kg VS added) achieved on semi-continuous co-digestion at loading rate of 2 kg VS /m^3.d in continuously stirred tank reactors at 35 ^{0}C were 0.21–0.24 at 85:15 and 0.30–0.33 at 80:20 (VS% pig manure to VS% potato co-substrate) feed ratio. Increasing the loading rate from 2 to 3 kgVS /m^3.d at a feed VS ratio of 80:20 (pig manure to potato waste) produced methane yields of 0.28–0.30m^3 / kgVS added.

According to a study of Alvarez and Lidén (2008), conducted with codigestion of manure and FVW, the methane yield increased from 0.14 to 0.34 m^3 /kg VS added when the OLR increased from 0.14 to 0.49 kgVS /m^3.day; however it decreased from 0.34 to 0.12 m^3 /kg VS at 3.8 kgVS /m^3.d.

2.1.6 Food waste and anaerobic digestion

Food processing factories produce quite large quantities of wastes that could potentially be treated through anaerobic digestion; because of their high content of organic biodegradable matter and relatively high content of water. However, anaerobic digestion of food wastes can pose a number of problems because of nutrient imbalance, rapid acidification, and presence of inhibiting compounds. (Carucci et al., 2005)

There are a number of technical constraints associated with anaerobic digestion of food waste. In fact, this high calorie substrate is easily degraded by fermentative bacteria, which produce large amounts of organic acids, that lower the pH in the reactor inhibiting the methanogenic system and limiting the generation of significant amounts of CH_4 (Vavilin et al., 2006; Bouallagui et al., 2004; Wang et al., 1997). Kim et al. (2004) reported that anaerobic treatment of food waste was not effective due to VFA accumulation, which resulted from the extremely high biodegradability of this waste. However, if used in co-digestion with sewage sludge, food waste improved nutrient balance and biodegradability. Thus, research at a laboratory scale is necessary for determining the operational parameters at full scale, also taking into account that anaerobic digestion has to face the high heterogeneity and seasonality of food production that eventually determine the waste composition.

Food waste is not very suitable to be mono-digested due to the hydrolysis rate and subsequent level of VFA accumulation. In order to avoid probable digestion failure, the best approach is to be co-digested with other waste with sufficient buffer capacity. Also, the addition of food waste to a process with low CH_4 yield will benefit the process. The answer to improve CH_4 production might be how to modulate the feed of anaerobic digestion.

Waste related to the food stream is regularly described as a good co-substrate. Sosnowski et al. (2008) compared the mesophilic co-digestion of a simulated OFMSW (25%) and activated sludge (75%) with the mono-digestion of the wastes. The composition of the simulated OFMSW was as follows: 55% of potato, 28% of fruit and vegetables, 5% of bread, 2% of paper plus 10% of rice and 10% pasta in weight. The cumulative biogas production for sewage sludge (0.181 m^3) was lower than that for co-digestion (0.232 m^3) or than the simulated OFMSW (0.228 m^3). During the fermentation of the latter, accumulation of VFA caused pH decrease and strongly inhibited gas production. The addition of activated sludge improved the buffering capacity of the system. The results indicated that if used in the proper proportion, activated sludge and OFMSW could be co-digested efficiently in existing municipal sewage sludge digesters that are operated under low load conditions. Similar work plan was used by Romano and Zhang (2008), reaching similar conclusions. The composition of the simulated OFMSW used by these authors was as follows: kitchen, vegetable market and yard waste.

2.1.7 Greenhouse Effects

The threatening global climate change calls for international efforts to reduce emissions of greenhouse gases (GHG), mostly CO_2, CH_4, and N_2O. The extent to which the emissions of different GHG contribute to the global warming are calculated in CO_2 equivalents (CO_2 eq.), using the global warming potential (GWP) of the different gases as proposed by the International Panel on Climatic Change (IPCC 1995, 1996). Since different GHGs have different efficiencies in heat adsorption and different lifetimes in the atmosphere, the GWP for every gas depends on the chosen planned time horizon. The GWP of CH_4 for a time horizon of 20 years is 56 (compared with CO_2 over the same period of time) and 21 for 100 years. This means that 1 ton of methane has the same impact on global warming over 100 years as does 21 tonnes of carbon dioxide (CO_2).

The increased concern about environmental problems caused by inadequate waste management, as well as the concern about global warming, promotes actions toward a sustainable management of the organic fraction of the waste (Ayalon et al., 2001). European Union Commission (2009) declares that improving the management of bio-waste will contribute, on the one hand, to a sustainable management of resources and to improved protection of soil and, on the other, to the fight against climate change and to reaching the targets for landfill diversion, recycling and renewable energy (EC, 2009).

Biogas, a clean and renewable form of bioenergy could very well substitute for conventional sources of energy (fossil fuels, oil, etc.) which are causing ecological and environmental problems; and at the same time are depleting at a faster rate (Yadvika et al., 2004). Greenhouse gas emissions, including CO_2 emissions, from renewable energy sources such as anaerobic digestion are either low or zero (EC, 2009). Moreover, since the feedstock for anaerobic digestion is a renewable resource, it does not deplete finite fossil fuels; such that the energy generated through this process can help reduce the demand for fossil fuels. The use of the fibre and liquor as a contribution to fertiliser regimes can also in turn reduce fossil fuel consumption in the production of synthetic fertilisers. (British Biogen, 1997)

The ultimate goal of bioenergy production is to minimize the amount of methane (CH4) by converting it to carbondioxide (CO_2). This can be achieved by physicochemical means (e.g., landfill gas flare, incineration) or by biological processes (e.g., composting, anaerobic digestion) (Ayalon et al., 2001). In other words; biomass is firstly digested into CH_4 containing biogas through anaerobic digestion; and this biogas is then utilized as energy and thus converted into CO_2. Current disposal practices for slurry and food residues cause methane to be released through natural processes. AD exploits this process so that the gas can be used as a fuel. A well-managed AD scheme will aim to maximise methane generation, but not release any gas to the atmosphere, thereby reducing overall emissions (British Biogen, 1997) .

Flaring is the inexpensive method often used to reduce the harmful effect of this greenhouse gas. However, capturing and then utilizing the methane as boiler fuel has added benefits, among others: compliance with environmental standards in effluents discharged, reduction in fugitive methane emissions that cause global warming, and creation of an alternative to fossil fuels in the production of steam and/or electricity (Custodio et al., 2006).

2.2 Snacks Production Industry

2.2.1 Snacks production

Snacks plants mainly manufacture three main types of snacks, namely:

a) Potato Chips- (PC) ,
b) Tortilla (Corn) Chips- (TC) , and
c) Extruded products from corn grain

Potato Chips Production

Potato chips production starts with raw potato intake and potato preparation. Potato is unloaded from the trucks to the intake unit, where it is firstly selected according to the sizing specifications. Potatoes with a size other than is determined by the specification is selected and scrapped, along with the soil, grass, and similar foreign material that may be present in the lot. Sized potato is then carried to the process area via conveyor belts.

Potato is washed, destoned and then peeled by automatic peelers. It is then subjected to another selection, where operators discard rotten or defected potatoes from the line. Peeled and selected potatoes are conveyed to the slicers. Slicing is performed according to the desired product specifications. Sliced potatoes arrive to the washing basin where they are re-washed. Water effluent from this process is sent to starch recovery unit, as the potatoes continue for the fryer. Potatoes are fryed, excess oil is seperated and then quality controlled; before being seasoned for the desired flavor. After flavoring, the chips is ready to be packed and sent to the markets. Figure 2.4 summarizes the potato chips production process.

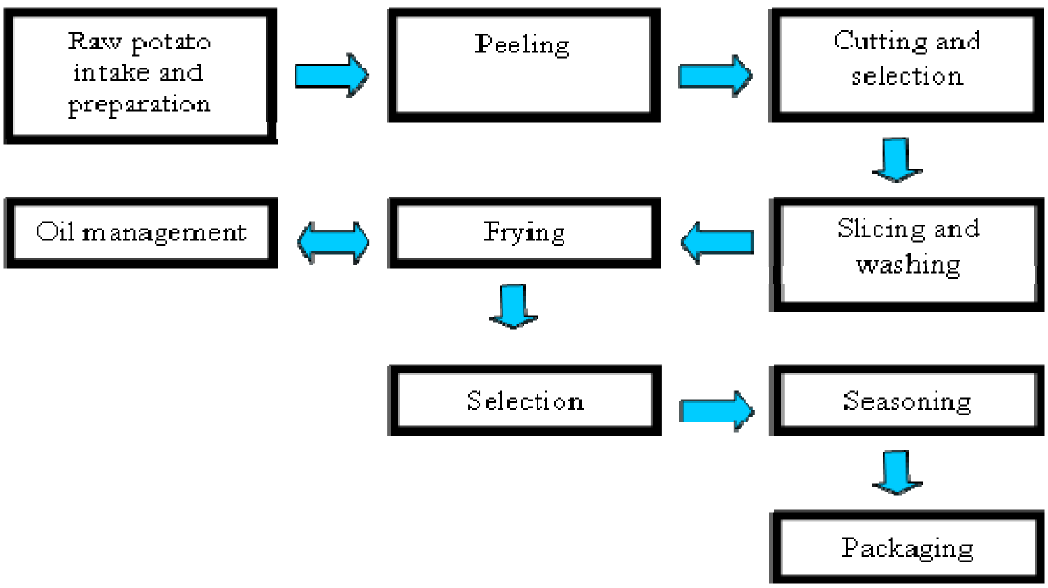

Fig 2.4 Potato chips production process flow chart

Tortilla Chips Production

Corn silos received from the depot are firstly cleaned off from debris, stones, broken or out-of-specification corn, dust, etc. Prepared corn is weighed and conveyed to cooking tanks. After cooking, the corn is marinated and sent to washing basin. Corn peels are removed in the washing basin, and the corn is ready for grinding. Grinded corn is shaped for the desired product and conditioned (cooled). After conditioning, the corn is fried, cooled in the oven and seasoned for the desired taste. After flavoring, the chips is ready to be packed and sent to the markets. Figure 2.5 summarizes the corn (tortilla) chips production process.

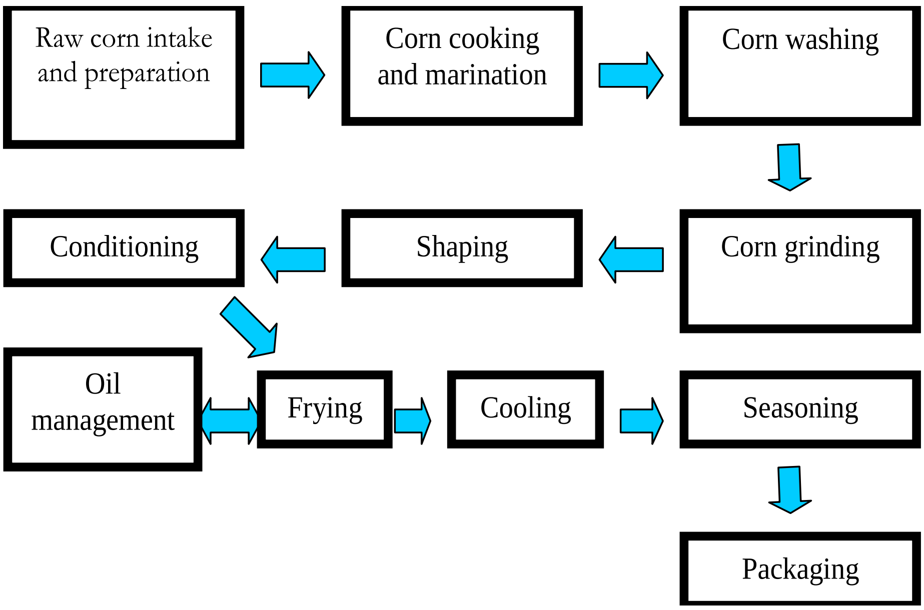

Fig 2.5 Tortilla (Corn) chips production process flow chart

Extruded Chips Production

Extruded chips products can be of two types; baked or fried. Below processes for each are provided:

Baked Extruded Chips Production

Corn grain is loaded to the extrusion unit. The extrusion process involves the explosion of corn grain under high temperature and pressure, while taking the shape of the specific product mould. By-product coming out of the extruder is baked in ovens and seasoned for the desired taste. After flavoring, the chips is ready to be packed and sent to the markets. Figure 2.6 summarizes the baked extruded chips production process.

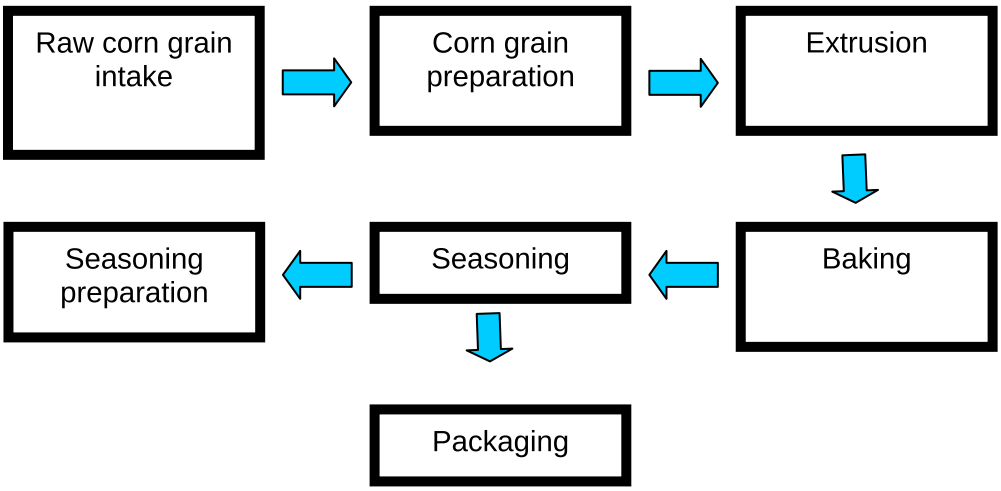

Fig 2.6 Baked extruded chips production process flow chart

Fried Extruded Chips Production

Fried extruded chips production involves the same processes summarized above; except for the by-product is fried, instead of being baked. Figure 2.7 summarizes the baked extruded chips production process.

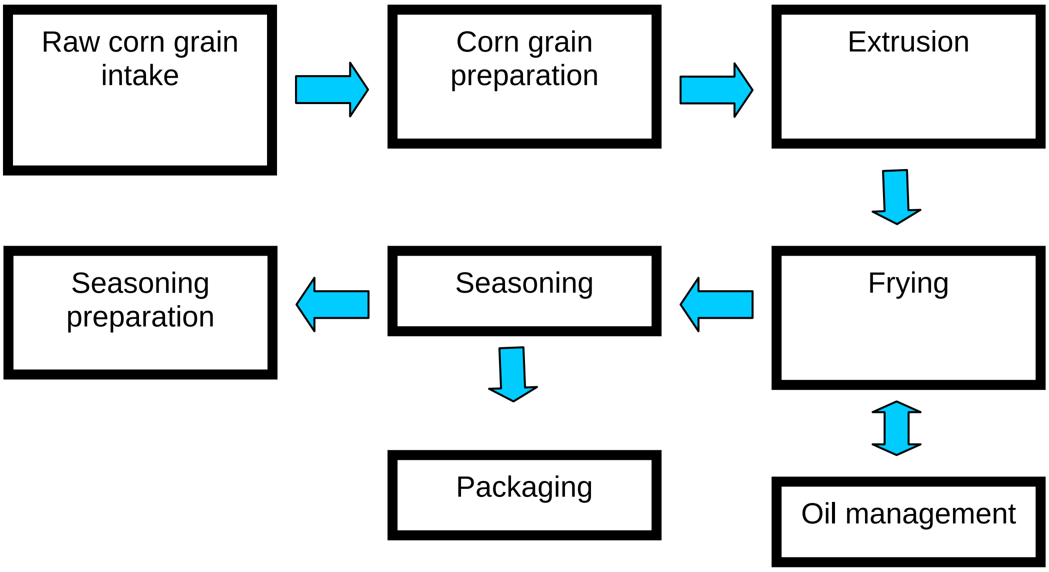

Fig 2.7 Fried extruded chips production process flow chart

The Plant of concern comprises of a potato chips (PC) line; two tortilla chips (TC) lines; and 3 extrusion lines. Annual production volume is 11000 tonnes of potato chips, 9000 tonnes of tortilla chips; and 11000 tonnes of extruded products on average. Basic raw material usage per annum is provided in the table below:

Table 2.2 Raw material used in the plant

Raw material	**Unit**	**Amount**
Potatoes	(ton/yr)	35000
Vegetable oil	(ton/yr)	8250
Salt	(ton/yr)	100
Seasoning	(ton/yr)	2250
Corn	(ton/yr)	7850
Corn Grain	(ton/yr)	6250
Cardboard	(pieces / yr)	4000000
Packaging material (OPP)	(ton/yr)	1800

2.2.2 Organic waste generation and handling

Agro-industrial wastes could be a serious environmental concern if they are not properly handled. Therefore, the agro-industrial wastes should be treated with the most economical and efficient technologies before their disposal into the surrounding environments (Demirer et al., 2000).

The EU countries have agreed on a directive stating that the amount of biodegradable organic waste that is deposited in landfills should be decreased by 65% by July 2016 (Council Directive 1999/31/EC on the landfill of waste, 1999). Actually, the agro-food industry provides interesting opportunities for the application of anaerobic digestion concept, in particular, due to the water consumption levels and wastes involved (Catarino et al., 2007; Darlington et al., 2009). Currently there is no regulation in Turkey regarding disposal or recycling of biodegradable organic waste; however being a country on the journey for joining the European Union, Turkey the topic will be an issue for regulatory and statuary requirements.

Since the snack manufacturing process mainly involves utilization of organic raw material; approximately 95% of all the waste generated in the plant is organic. The remaining 5% of the waste is made up of hazardous waste (such as laboratory kits, chemical containers, machinery oil and grease, medical waste, batteries, flourescent lamps, electronical waste, etc), and packaging material.

Organic waste generated

Organic waste generated in the Plant of concern can be categorized in 2 groups:

- Process related
    - Raw material waste; such as corn, potatoes, corn grain
    - By-product waste; such as potato peels, corn dough,seasoning
    - Product waste; such as potato/tortilla chips
    - Waste vegetable oil
    - Starch from starch recovery unit
    - Oil trap residues

- Non-process related
    - Grass waste from landscaping
    - Wastewater sludge from WWTP

Actual organic waste generation rates for years 2007-2009, can be found in Table 2.3; and related percentage distribution chart in Figure 2.8 respectively:

Table 2.3. Organic waste generation rates in the Plant

Type of Waste	**2007 (ton/yr)**	**2008 (ton/yr)**	**2009 (ton/yr)**
Primary sludge	4.152	3.818	4.157
Excess activated sludge	337	310	337
Refused potatoes	972	1.020	1.022
Refused corn	73	32	77
Processed potato	2.208	2.255	2.361
Processed corn	45	46	49
Scrap products	1.715	1.577	1.717
Other organic waste	540	496	540
Waste Vegetable oil*	50	50	50
TOTAL	10.092	10.054	10.310

* Waste Vegetable oil is to be handled in accordance with the "Regulation on Waste Vegetable Oil", issued by the Ministry of Forestry and Environment, 2005; Official Gazette number 25791. Thus, vegetable oil will not further be used for calculations and assessments related with "anaerobic co-digestion".

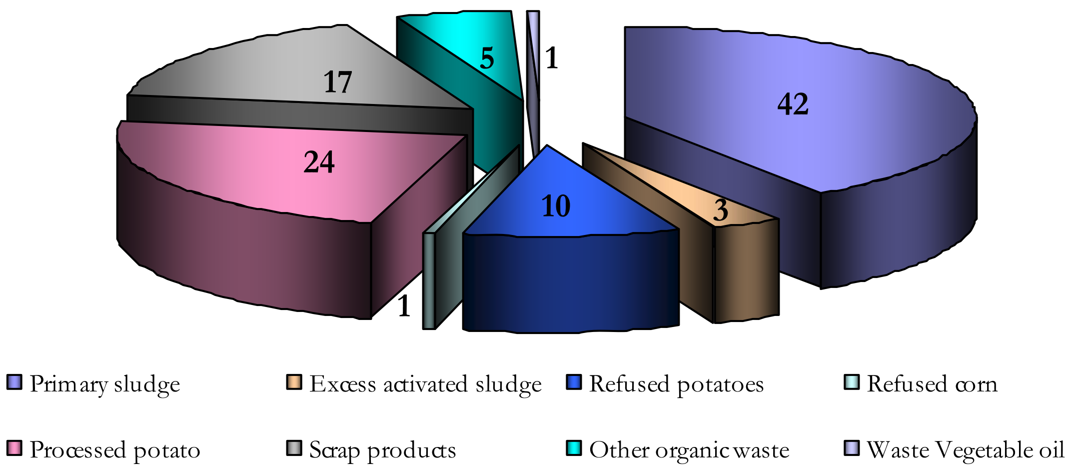

Fig 2.8 Percentage distribution of organic waste generated

Organic waste handling

Before the second half of year 2008; the organic waste generated in the Plant handled was as stated below:

- Raw material, by-product and product was used as animal feed
- WWTP sludge sent to farmers as soil conditioner
- Starch used for plaster manufacturing
- Vegetable oil used for biodiesel production
- Grass, seasoning and all the other organic waste was sent to İzaydaş as domestic waste.

During the period September 2008-September 2009, 1st stage ACF (1200 m^3 reactor) came into operation and 25% of the organic waste, except for starch and vegetable oil was utilized in the plant.

In September 2009, 2nd stage of the anaerobic co-digestion facility (ACF) came into operation, which has a capacity of utilizing 75% of the organic waste. Details of the ACF is provided in Chapter 2.2.4. Figure 2.9 depicts the schematic representation of organic waste utilized in the ACF :

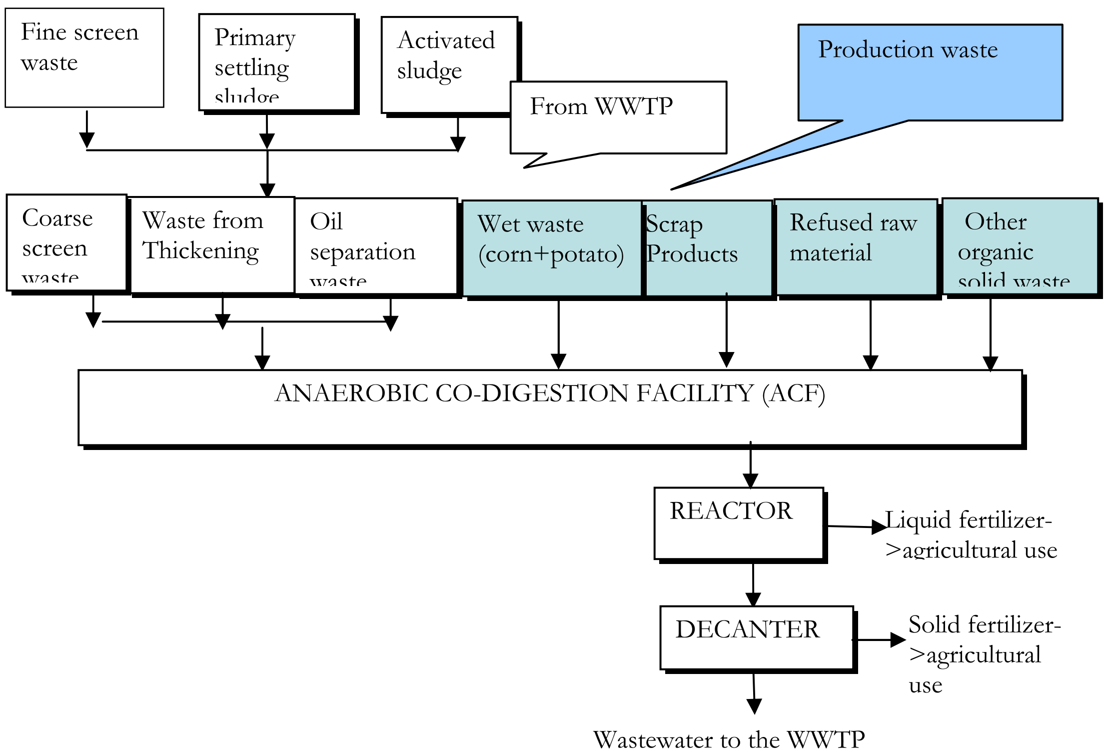

Figure 2.9: Schematic representation of organic waste utilized in the anaerobic co-digestion facility (ACF)

2.2.3 Wastewater generation and treatment

Wastewater generation

Snacks factories generate wastewater with high BOD and COD concentrations (Hadjivassilis et al., 1997). Since wastewater originating from a potato-processing plant contains high concentrations of biodegradable components such as starch and proteins; in addition to high concentrations of chemical oxygen demand (COD), total suspended solids (TSS) and total Kjeldahl Nitrogen (TKN), this industry could present serious environmental problems (Senturk et al., 2009).

In the processing of potato-chips, the wastewater formed generally from washing, peeling, slicing, and rinsing (Senturk et al., 2009).

Wastewater generated in various parts of the Plant can be categorized as follows:

a) Wastewater generating activities in PC Processes :

- Potato washing and destoning
- Peeling
- Slicing
- General sanitation activities

b) Wastewater generating activities in TC Processes :

- Corn cooking
- Corn washing
- General sanitation activities

c) Wastewater generating activities in Extrusion Processes :

- General sanitation activities

d) Wastewater generating activities besides production processes

- Boilers
- Cooling processes
- Water used for public purposes

Characteristics of the wastewater

WWTP influent chacracteristics of the Plant is summarized in the Table 2.4 below: Proving the literature, COD and BOD levels are high; with an average daily loading of 800 m^3 of wastewater / d.

Table 2.4 WWTP influent characteristics

Parameter	Value (mg/L)
Total Suspended Solids	4320
BOD_5	3550
COD	9480

Table 2.5 shows the wastewater flow resulting from different processes in the plant

Table 2.5 Wastewater amount resulting from different processes

Wastewater type	Flow (m^3 / d)	$Q_{influent}$ (m^3/d)
Process Wastewater		
a) PC	400	400
b) TC	400	400
Bluff water (boiler)	0.5 – 1	
Total	800	800

Wastewater treatment plant

The WWTP treating the Plant's process water, consists of physical, biological (aerobic and anaerobic); and sludge treatment units. Process flow of the WWTP is given in Figure 2.10.

Physical treatment units consist of step screen, rotary screen, dissolved air flotation, fast and slow mixing, primary settling tank and the neutralization tank .Solid particles present in the wastewater are removed through physical treatment. 81% of oil and grease; nearly 30 % of COD and 50% of TSS is removed by physical treatment units.

Biological treatment follows the physical treatment unit. It consists of anaerobic treatment and aerobic treatment. The anaerobic reactor is an upflow anaerobic sludge blanket type (UASB) reactor. The UASB reactor was introduced at the beginning of 20th century, in the Netherlands, for the treatment of industrial wastewater generated by the food industry, mainly for beet sugar, corn and potato starch (Bitton, 1994). The UASB type of digester consists of a bottom layer of packed sludge, a sludge blanket, and an upper liquid layer. Wastewater flows through a sludge blanket of active bacterial flocs (Lettinga et al., 1980). Settler screens separate the sludge flocs, and gas is collected at the top of the reactor (Bitton, 1994). With this high-rate anaerobic process, COD removal efficiencies of 90–95% were achieved at OLRs ranging from 12 to 20 kg $COD/m^3.d$ (Tchobanoglous et al., 2003). The UASB unit removes 85 % of BOD_5 in this snack plant's wastewater. Biogas generated by the reactor flows through a chemical scrubber in order to remove H_2S and CO_2; and collected in the biogas holder.

Wastewater coming out of the anerobic treatment units is diverted to the aerobic treatment units. Aerobic reactors operate on the activated sludge process principle in sequencing batch reactors. The operation of SBR involves four steps: (1) feed, (2) react, (3) settle and (4) withdraw. Air is supplied through diffusers fed by blowers to the circular aeration tanks, where activated sludge is present. Activated sludge is aerated for 6 hours as it is being fed; and aeration goes on for another 3 hours after feeding is stopped. Sludge is left to settle for 2 hours, and the wastewater effluent is discharged. The overall BOD_5 and COD removal efficiency for the treatment units is approximately 99 %. Treatment efficiencies of different units of the Plant's WWTP are provided in Table 2.6; and resulting effluent quality parameters are provided in Table 2.7

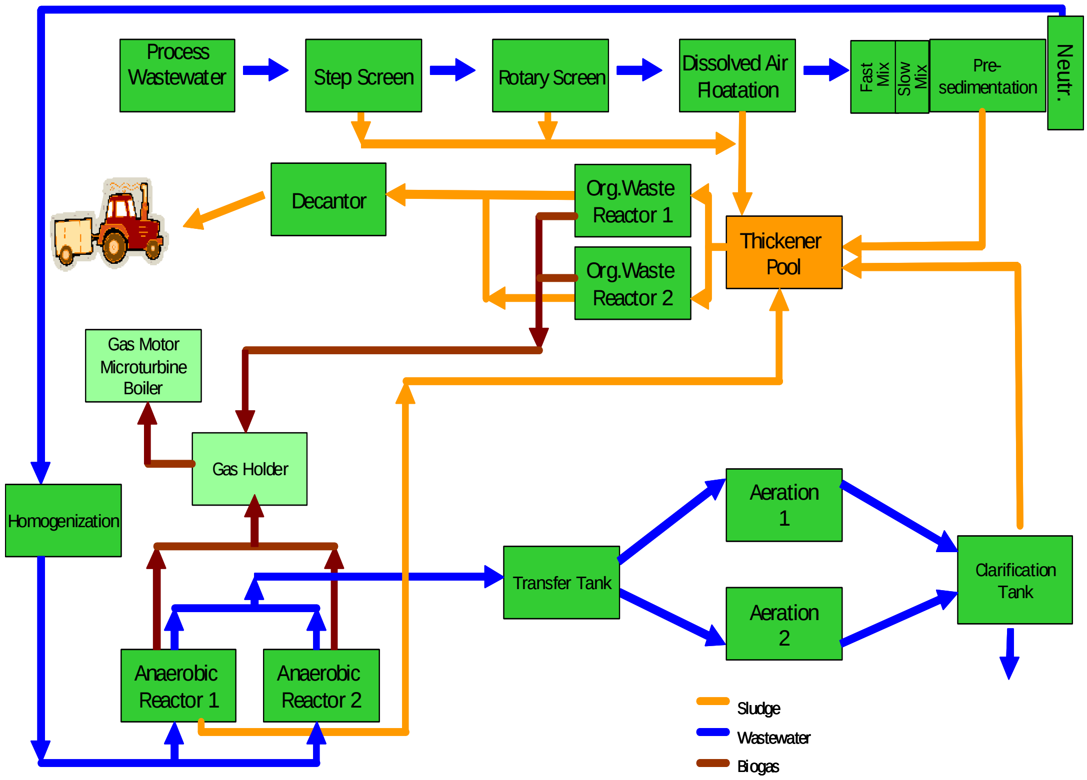

Figure 2.10 WWTP Process Flow

Table 2.6 Treatment Efficiencies of WWTP units

Unit	Treatment Efficiency (%)			
	TSS	BOD_5	COD	Oil and Grease
Equalization Basin	4.1	4	4	3.3
Physical Treatment	47.8	27.5	29	81
Anaerobic Treatment	30	85	70	5
Aerobic Treatment	97	87.8	94.8	4.3
Overall	98.9	98.7	98.9	83.3

Table 2.7 WWTP Effluent Characteristics

	TSS (mg /L)	**BOD_5 (mg / L)**	**COD (mg / L)**
Influent	4320	3550	9480
Equalization Basin	4140	3408	9100
Physical Treatment Effluent	2160	2470	6456
Anaerobic Treatment Effluent	1512	370	1936
Aerobic Treatment (Final) Effluent	25	45	100

2.2.4 Anaerobic co-digestion of wastewater sludge and organic waste

The anerobic co-digestion facility (ACF) is constructed by the existing wastewater treatment plant. The process in the ACF involves co-digestion of sludge from the WWTP (primary and waste activated sludge), together with the other organic waste produced in the factory. The anerobic co-digestion facility also uses some of the systems belonging to the existing WWTP, such as the gas holder and the flare. The construction of the ACF was planned in two stages:

- 1^{st} stage to be the 1200 m^3 anaerobic digester, and the
- 2^{nd} stage to be the full-scale 3000 m^3 anaerobic digester.

.

The ACF consisted of following main units:

- Sludge thickening tank (WWTP)
- Equalization basin

- Waste pumping station
- External heating system
- Chemical dosing system
- Anaerobic digester and mixer
- Fertilizer dewatering system and polimer dosing station
- Filtrate pumping station
- Biogas holder
- Chemical desulpherization (WWTP)
- Physical desulphurization
- Biogas pressuring system
- Micro-turbine co-generation unit (1st stage)
- Engine co-generation system (2nd stage)

Construction and commissioning of the 1st phase of the ACF was completed in August 2008 and it had been in operation since that time. 2nd stage of ACF construction and commissioning was completed in August 2009 and it is declared to be in operation since September 2009. Mass flow diagram of the ACF is provided on Figure 2.11 and cchematic representation of ACF is provided on Figure 2.12

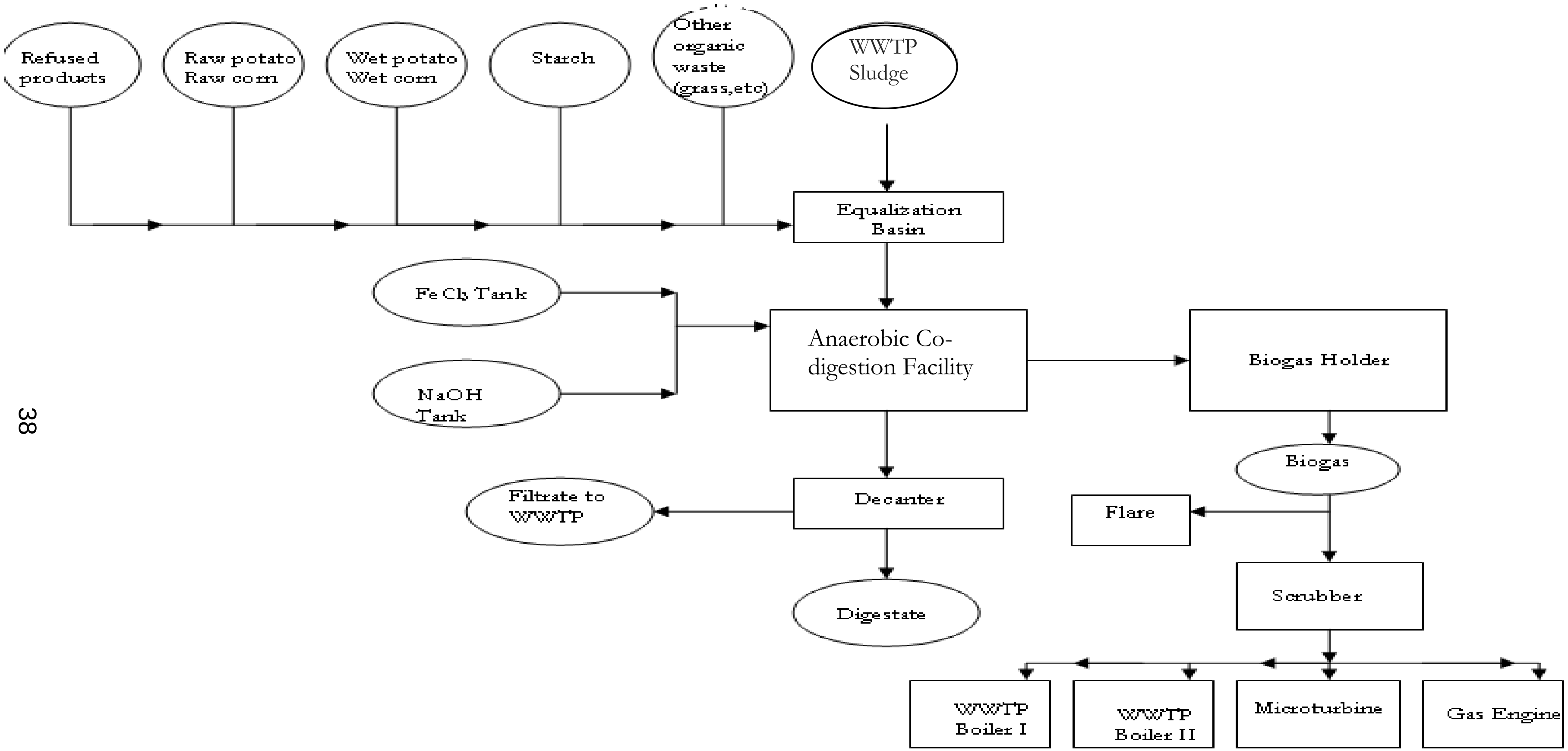

Figure 2.11 ACF process flow diagram

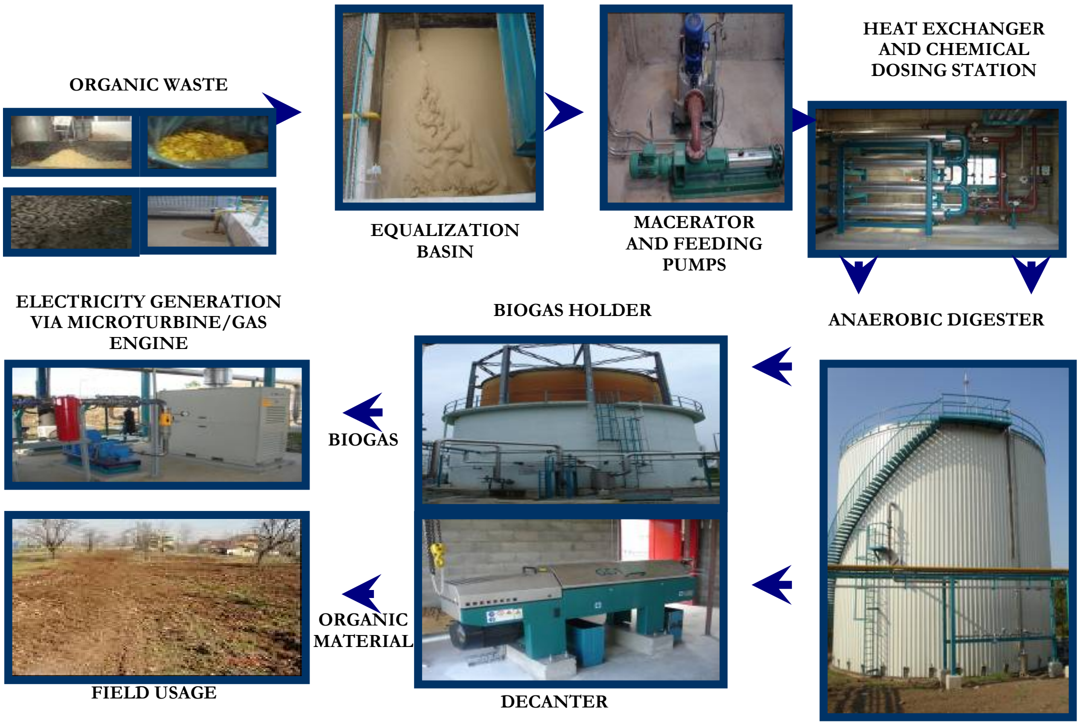

Figure 2.12 Schematic representation of ACF

2.2.4.1 Process Design Data

The process was designed according to the waste characteristics and quantities generated in the plant, which were depicted in Tables 2.8 and 2.9 respectively. Biogas yield, biogas production, energy production and fertilizer production were other factors considered for the design process; which were provided in preceding sections.

Table 2.8 Characteristics of the Different Waste Types

Waste type	Solid content (TS), %	Organic Content (VS/TS), %	C/N
WWTP Sludge (liquid form)	3,6	79	12,1
Green Waste (grass etc.)	18	86	9,7
Refused products (crisps)	99	96	18
Corn Wastes	29	96	14
Potato Wastes	20	97	13
Composite Wastes (Substrate)	10	90	15

Table 2.9 Waste Quantities

Waste Type	Flow 1st Stage (ton/d)	Flow 2nd Stage (ton/d)	Flow Total (ton/d)
WWTP Sludge (liquid form)	35	105	140
Green Waste (grass etc.)	0,3	0,9	1,2
Refused products (crisps)	1,8	5,3	7,2
Corn Waste	0,8	2,4	3,2
Potato Waste	5	15	20
Composite Waste (Substrate)	42,9	128,6	171,5

Biogas Yield

Biogas yields of waste streams have been calculated in Appendix A and are tabulated in Table 2.10

Table 2.10 Biogas Potential of Different Waste Types

Waste Type	Biogas Potential (m^3/ton VS) (A)	Solid content (TS), % (B)	Organic Content (VS/TS), % (C)	Biogas Potential (m^3/ton) (D)
WWTP Sludge (liquid form)	500[a]	3.6	79	14
Green Waste (grass etc.)	575*	18	86	109
Refused products (crisps)	525*	99	96	148
Corn Waste	500*	29	96	76
Potato Waste	500*	20	97	97
Composite Waste (Substrate)	525[b]	10	90	34

*Deublein and Steinhauser, 2008

[a] WWTP sludge consists mainly of potato and corn waste; hence biogas potential is assumed to be same as potato and corn waste

[b] Biogas potential of composite waste is calculated as the average of its constituents

2.2.4.2 Operating principles

The sludge produced in the existing WWTP was pumped to the equalization basin of the ACF, where it was mixed with the organic waste produced in the plant. The organic waste was transferred with forklift containers and added to the equalization basin.

Figure 2.13 Forklift carrying Organic waste Figure 2.14 Equalization basin with mixer

The basin was equipped with a mixer that ensure that the various organic waste is . homogenously mixed. The ACF accepted all the organic waste material produced in the factory, such as:

- WWTP sludge
- Raw materials (potato, corn)
- Production waste (wet potato and corn)
- Refused products (crisps)
- Grass from landscaping in the factory territory

The waste mixture was then pumped to the anaerobic digester. A macerator in the pumping line cropped the material in small pieces in order to improve the biological activity in digester and to protect the equipment such as pumps and control instruments from large particles.

Figure 2.15 Reactor feeding pump and in-line macerator

The waste mixture was heated to the optimum temperature for the fermentation (30-35 ºC) process with the help of a heat exchanger. The necessary heat source was supplied from the co-generation unit that is burning the biogas generated in the digester.

Figure 2.16 Heat Exchanger

The ACF was equipped with a chemical dosing station. Caustic (NaOH) was used in start-up to improve the pH and $FeCl_3$ is used to minimize the H_2S in the biogas, which could be harmful for the co-generation unit.

Figure 2.17 Chemical Dosing Station

2.2.4.3 Anaerobic co-digestion

Anaerobic digestion involves the biological decomposition of the organic substances by bacteria in the absence of oxygen. Digestion process is carried in a closed steel tank, under the control of the process parameters such as the temperature, pH, pressure, organic load.

During the decomposition organic substances are converted into CH_4 and CO_2, the mixture of which is called the *biogas*. Biogas due its methane content has high calorific value and can be used in the production of energy by burning in a generator.

As a result of the anaerobic digestion the chemical properties of the substance are altered resulting in improved soil conditioner or fertilizer characteristics. Nitrogen entrapped in the long-chain molecules convert into the form of ammonium which is more easily captured and utilized by plants. Additionally removal of carbon creates a lower C/N ratio, which increases in this particular application the fertilizer value of the product. During the digestion process approximateley 50 – 60 % of the organic material is decomposed. The residual organic material is also valuable to be considered as organic fertilizer.

The ACF's anaerobic digester was a cylindrical reactor equipped with a mixer, which was sufficient for the decomposition of almost all degradable organics. Proper mixing of the AD is essential for providing an optimum performance. Mixing provides intimate contact between the feed sludge and active biomass, yielding uniformity of temperature, of substrate concentration, of other chemical, physical and biological aspects throughout the digester, and preventing both the formation of surface scum layers and the deposition of sludge on the bottom of the tank (Appels et al., 2008).

The retention time of the waste in the reactor was 20 days on average (see Chapter 4.2 for details).

Figure 2.18 Anaerobic Digester

Figure 2.19 Top-entry Anaerobic Reactor Mixer

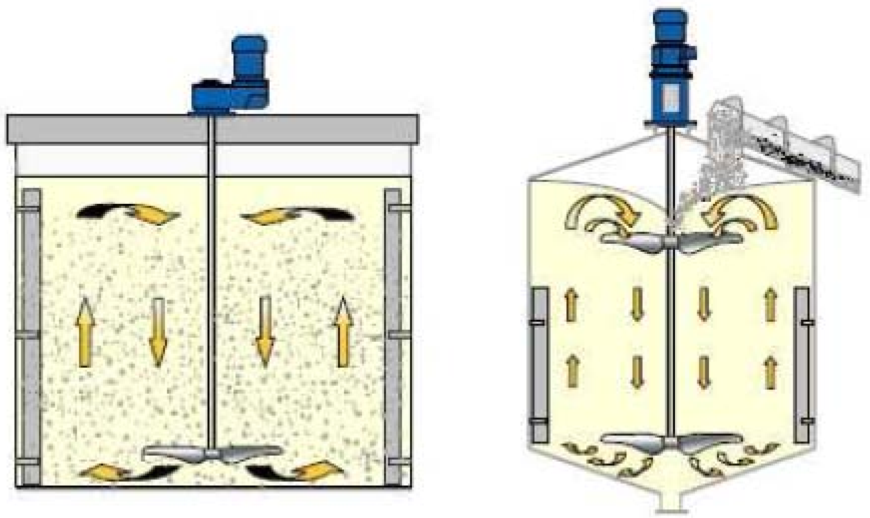

Figure 2.20 Top-entry Anaerobic Reactor Mixer's Operation Principle

2.2.4.4 Biogas Handling and Co-generation

The produced biogas was transferred to the existing biogas holder, where also biogas from the wastewater treatment plant was collected. The biogas holder was chosen to be a floating top type since it was stable and durable. Capacity of the biogas holder was 400 m^3.

Figure 2.21 Floating Top Biogas Holder

Figure 2.22 Biogas measurement and monitoring instruments

The collected biogas was utilized in the existing boilers and the co-generation system. Before feeding to the co-generation, biogas went through a water scrubber unit in order to minimize the sulphur content, which might be harmful for the generator.

First stage of the ACF generated heat and electricity via a micro-turbine with an electrical capacity of 65 kW and a heat capacity of 100 kW. The produced electricity and heat covered all of the ACF's energy consumption. The excess energy was utilized for the wastewater treatment plant's energy needs.

Figure 2.23 65 kWe Micro-turbine Co-generation Plant and Accessories installed (1st Stage)

Second stage (3000 m^3) of ACF generated heat and electricity via an engine co-generation plant that had a capacity of generating 330 kW electrical and 330 kW heat generation capacity.

Figure 2.24 330 kWe Gas Engine Co-generation Plant

CHAPTER 3

MATERIALS AND METHODS

3.1 Inoculum and substrate cultures

Three different sets of inoculum and three different sets of substrate cultures were used for Experiments I, II and III. All the inoculum and substrate cultures consisted of sludge from wastewater treatment plant, along with organic waste from the manufacturing process; only in different ratios. For Experiment I, sludge was obtained from the sludge thickening tank, and was inoculated to the reactor along with organic waste mentioned above. For Experiments II and III; inoculate was taken directly from the ACF. Substrate was collected for weekly usage and stored at $0\,^{o}C$ in the refrigerator. Inoculum material was used for the start-up of reactors; whereas substrate was used for feeding purposes. Detailed characteristics of the media are provided below:

- Inoculum and substrate characteristics used for Experiment I are given in Tables 3.1 and 3.2 respectively.

Table 3.1 Experiment I - Inoculum Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	87	5.5	88
Potato waste (wet)	4	25	95
Corn waste (wet)	4	25	95
Refused products	5	97.5	95
Total mixture	100	11.7	92.1

Table 3.2 Experiment I - Substrate Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	90	5.5	88
Potato waste (wet)	6.5	25	95
Corn waste (wet)	0.5	25	95
Refused products	3	97.5	95
Total mixture	100	9.6	91.4

- Inoculum and substrate characteristics used for Experiment II are given in Table 3.3 and 3.4 respectively.

Table 3.3 Experiment II - Inoculum Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	90	5.5	88
Potato waste (wet)	6.5	25	95
Corn waste (wet)	0.5	25	95
Refused products	3	97.5	95
Total mixture	100	9.6	95

Table 3.4 Experiment II – Substrate Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	82	5.5	88
Potato waste (wet)	5.5	25	95
Corn waste (wet)	0.5	25	95
Refused products	6	97.5	95
Starch	6	92	90
Total mixture	100	17.4	91.6

- Inoculum and substrate characteristics used for Experiment III are given in Table 3.5 and 3.6 respectively.

Table 3.5 Experiment III - Inoculum Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	90	5.5	88
Potato waste (wet)	5.5	25	95
Corn waste (wet)	0.5	25	95
Refused products	4	97.5	95
Total mixture	100	10.4	91.7

Table 3.6 Experiment III – Substrate Characteristics

Waste stream	**% in mixture**	**% TSS**	**% VSS/TSS**
WWTP sludge	82	5.5	88
Potato waste (wet)	7	25	95
Corn waste (wet)	2	25	95
Refused products	7	97.5	95
Starch	2	92	90
Total mixture	100	15.4	92.4

3.2 Experimental set-up

The experimental set-up used is depicted in Figure 3.1 The process used for the experimental set-up was a mesophilic wet anaerobic digestion process. The anaerobic digester was a closed tank with an optimum operating temperature of 35 – 37 ºC and a pH of 6.8 – 7.5.

A reactor of having an effective volume of 90 L (R1) was used for Experiment I and II; whereas a reactor of 190 L (R2) was used for Experiment III.

The reactor was fed daily. The waste was supplied to the reactor from top. The feeding pipe went below the water level, such that no leakage of biogas could occur. The reactor was a continuously stirred tank reactor (CSTR), and the content was mixed continuously with the aid of a vertical mixer. As the feeding material was loaded to the reactor, same amount of sludge was discharged from the reactor. The mixer was stopped during loading process, in order to prevent escaping of sludge. There was no sludge recycling process; hence the Hydraulic Retention Time (HRT), was equal to Solids Retention Time (SRT).

The reactor had a side-entry electrical heater, which had a temperature sensor and control mechanism to keep the inlet temperature of the reactor between 35 – 37 ºC.

The pressure of the reactor was observed by the manometer. The produced biogas was discharged from the top of the reactor and entered the biogas holder from the bottom. The biogas holder was a floating tank, where the weight of the floating top part was chosen according to the desired pressure of the biogas to be stored. As two tanks were inter-connected, the biogas pressure in the gas holder and in the reactor had to be the same. The pressure of the system could be adjusted by adding or removing weight on top of the floating tank. Design pressure value for the set-up was 1.2 bar.

When the biogas holder was full (the floating top was at maximum height), the biogas discharge valve was opened manually, and the biogas was released via the biogas flow meter.

When biogas production commenced in the reactor, the biogas pressure started to increase. This causes the water level in the biogas holder (outside the floating tank) to rise. The rise can be observed as the interior wall is scaled. The water level rised until the pressure is the same as the weight of the floating tank. Then the water level is fixed (y maximum.) and than the floating tank starts to rise until the maximum. point (x maximum).

The temperature of the reactor was observed from the thermometer on the reactor wall. The pH value was measured by a manual pH meter on the samples taken from the reactor discharge valve. Photographs of the experimental set-up and related instruments are provided in Figures 3.2 – 3.5

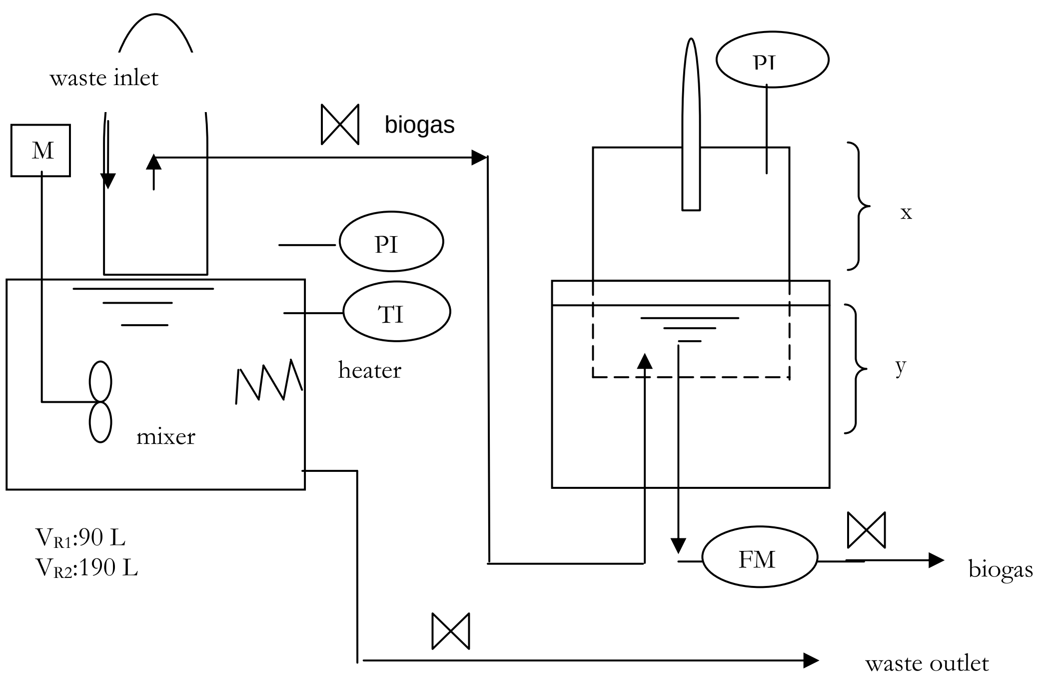

Figure 3.1 The experimental set-up

Where;

FM : Biogas flow meter

PI : Manometer

TI : Thermometer

x : Height of the gas holder top part

y : Water level in the gas holder bottom part

Figure 3.2 Experimental set-up

Figure 3.3 The thermometer

Figure 3.4 The manometer

Figure 3.5 Reactor inlet

Three sets of experiments were performed, where the digesters were fed with OLRs of 3.3 ; 5.3 and 6.4 kg VS/m^3. d respectively. Before the onset of daily feeding, R1 was operated for 26 and 6 days for experiments I and II respectively. R2 was operated for 7 days before starting daily feeding. The time period that elapsed between inoculation and feeding was the time that passed for the reactors to reach steady-state biogas production. The difference between the elapsed time for the experiments results from the inoculate material fed to the reactor. When steady-state conditions were achieved in the reactor, feeding with the substrate commenced. In order to prevent overloading of reactors, VFA concentration was measured before feeding the reactor, and feeding was performed if it was below 5 meq/L (75 mg/L as acetic acid).

R1 was operated for Experiment I and II; and R2 was operated for Experiment III. Figure 3.6 shows inoculation of the reactor. Summary of operational parameters can be found in Table 3.7.

.

Figure 3.6 Inoculation process

Performance of the experiments was monitored by measuring biogas production, Chemical Oxygen Demand (COD), Volatile Fatty Acid (VFA) concentration, Volatile Solids and pH. Total Nitrogen (TN) and Total Phosphorus (P) measurements were also conducted by the beginning and at the end of experiments.

Table 3.7 Summary of operational parameters

Experiment No.	HRT (days)	C_{in} (g VS/L)	V_{in}/V_r (L/L)	OLR (kg VS/m^3.d)
I	30	100	3/90	3.3
II	30	160	3/90	5.3
III	30	142	8.5/190	6.4

C_{in}: Sludge concentration fed to the reactor, V_{in}: Volume of sludge fed to the reactor, V_r: Volume of reactor

3.3 Analytical methods

VFA, COD, TS, VS, Total nitrogen, Total phosphorus and dry matter analyses were performed at the snacks plant's wastewater laboratory (Suadiye/Kocaeli). Frequency of analyses can be found in Table 3.8

Table 3.8 Frequency of analyses

Parameter	Frequency	Inlet (I)/Outlet (O)
COD	Daily	I / O
TSS	Daily	I / O
VSS	Daily	I / O
TP	Start and end of experiment	I / O
TN	Start and end of experiment	I / O
VFA	Daily	O
Biogas production rate	Daily	O
Biogas composition	Every two weeks	O

Volatile Fatty Acids (VFA)

Standard method 5560 B (APHA, 2005) was used for VFA measurement. 0.10 N HCl was added to the centrifuged sample until the pH dropped down to 3. Bicarbonate was thoroughly converted into CO_2 and volatile fatty acid with this reaction. CO_2 was removed by boiling the sample in the reflux column. Sample was then titrated with 0.10 N HCl to pH 6.5. Volatile fatty acids and weak acids were thus dissolved. VFA and bicarbonate values were calculated by the acid and alkali amount used as given in Equation 3.1:

$$VFA = \frac{(bx101) - (a + 100)}{99.23} x \frac{100}{V} = meq / lt \qquad (3.1)$$

b : 0.1 N NaOH used

a : 0.1 N HCl used

V : Sample volume

Chemical Oxygen Demand (COD)

COD analyses were performed with EPA approved reactor digestion method (for a COD range of 0-1500 mg/L) and spectrophotometric determinations were performed by using Hach-Lange DR 2500 Spectrophotometer.

Total Solids (TS)

Standard method SM 2540 B was used for TSS measurement. Total Solids dried at 103–105 °C (APHA, 2005) :

$$TSS(mg / lt) = \frac{(B - A)x1.000}{5} \; ; \qquad (3.2)$$

Where;

A: Weight of filter paper

B: Weight of sample (filter paper+sediment)

Volatile Solids (VS)

Standard method SM 2540 E was used for VSS measurement 2540 E. Fixed and Volatile Solids Ignited at 550 °C (APHA, 2005) :

$$VSS(mg/lt) = \frac{(B-C)x1.000}{5} \; ; \tag{3.3}$$

Where;
B: Weight of sample (filter paper+sediment) from the TSS experiment
C: Weight of filter paper+sediment after dryed in the oven.

Total Phosphorus

Total Phosphorus was measured by EPA approved reactor digestion method (for a phosphorus range of 0-100 mg/L) and spectrophotometric determinations were performed by using Hach-Lange DR 2500 Spectrophotometer. CAT 27672-45 Hach-Lange standard kit was used for the light spectrophotometry.

Total Nitrogen

Total Nitrogen was measured by EPA approved reactor digestion method (for a nitrogen range of 10-150 mg/L) and spectrophotometric determinations were performed by using Hach-Lange DR 2500 Spectrophotometer. CAT 26721-45 Hach-Lange standard kit was used for the light spectrophotometry.

Biogas production rate

Biogas production rate was measured via the flowmeter mounted on the biogas holder.

Temperature and pH

Temperature and pH values were observed through the instruments mounted on the digester.

Biogas composition analysis

Biogas composition analysis was performed with portable gas analyser Gas Data LMSxi G2.18.

The analyser could measure:

- CH_4 content(%)
- CO_2 content (%)
- O_2 content (%)
- H_2S content (ppm)

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results of OLR Experiments

Three different OLRs; namely 3.3; 5.3 and 6.4 kg VS / m^3.d were tested in the experimental set-up and results are provided below, categorized for biogas yield, pH, COD removal, VS removal, nitrogen and phosphorus, and biogas composition.

4.1.1 Biogas yield

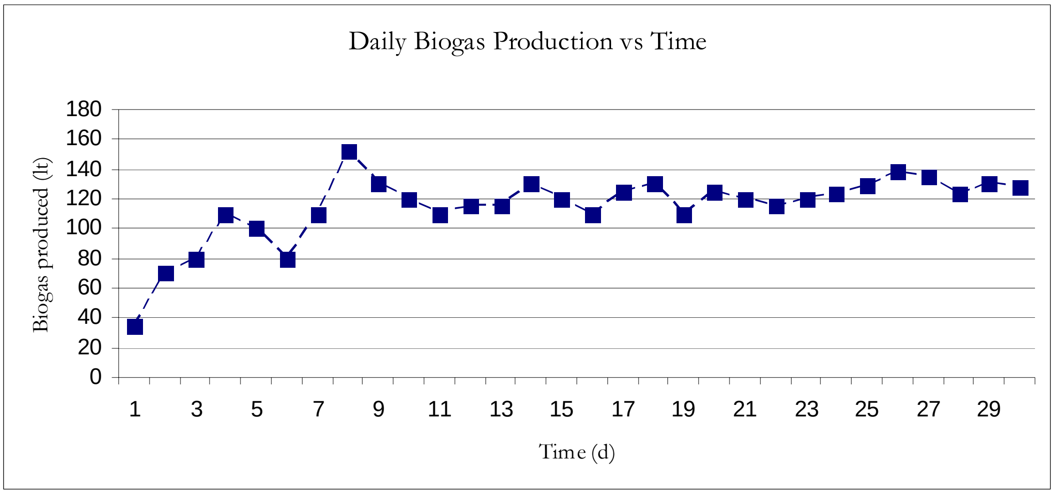

Figure 4.1 Daily biogas produced vs. time, OLR = 3.3 kg VS / m^3.d (■)

The operation started with an organic loading rate (OLR) of 3.3 kg VS / m^3.d. The biogas production rate and biogas yield at this OLR averaged 114 L/day; with a peak value of 152 L/day on day 8; and 0.396 L/g VS added respectively. Daily biogas production values can be found in Figure 4.1.

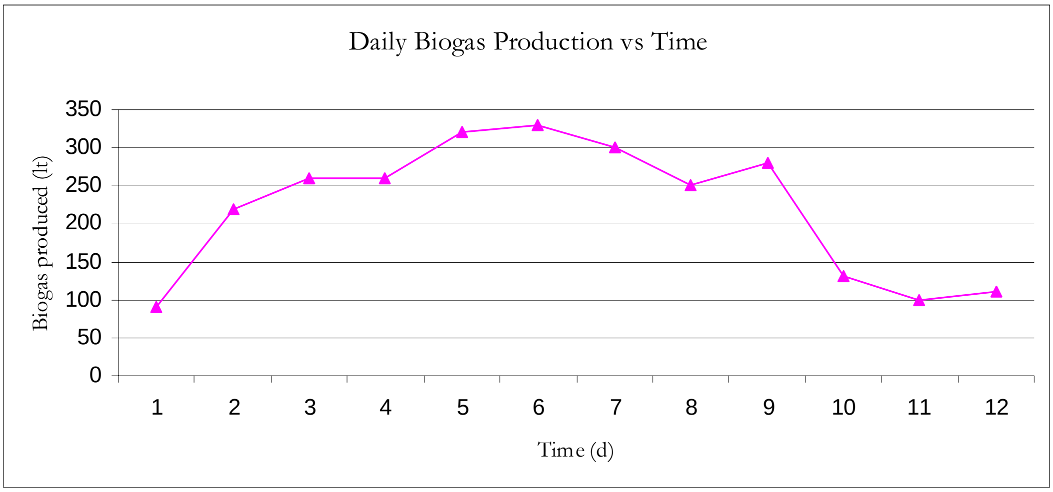

Figure 4.2 Daily biogas produced vs. time, OLR = 5.3 kg VS / m^3.d (▲)

Organic loading rate (OLR) is increased to 5.3 kg VS / m^3.d, in order to investigate the effects of higher OLRs, after experimenting 30 days with 3.3 kg VS/ m^3.d. The biogas production rate and biogas yield at this OLR averaged 207 L/d and 0.431 L / g VS added respectively. Daily biogas production values can be found in Figure 4.2. Biogas production peaked with a value of 330 L/d, on day 6. Biogas production decreased from 280 L/d to 130 L/d between days 9 and 10; and the situation was investigated. The dropdown in the biogas production continued in days 11 and 12, though no changes in pH or VFA were observed. Suspecting that there might be a leakage from the reactor; foam test was applied and it was found out that biogas was leaking from the reactor. Hence, the experiment was ended.

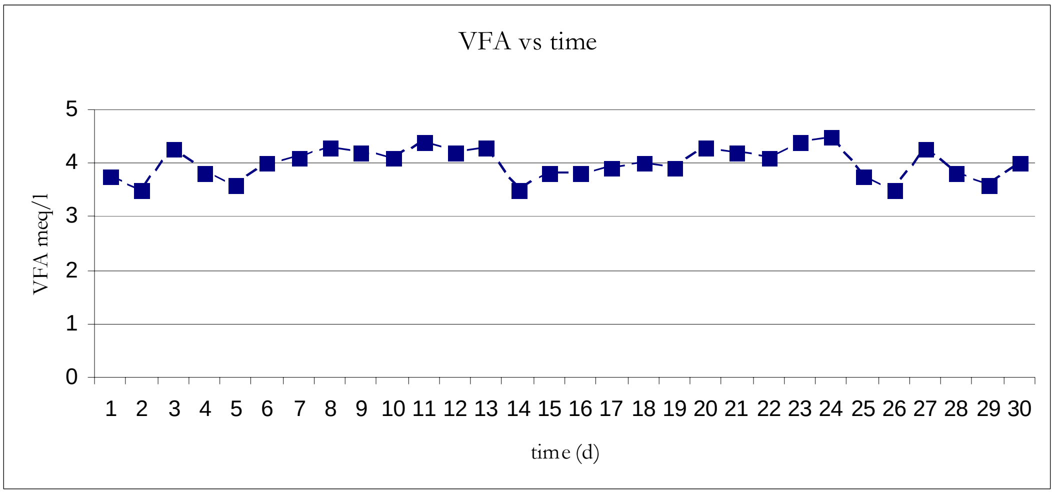

Figure 4.3 VFA vs. time, OLR = 3.3 kg VS / m^3.d (■)

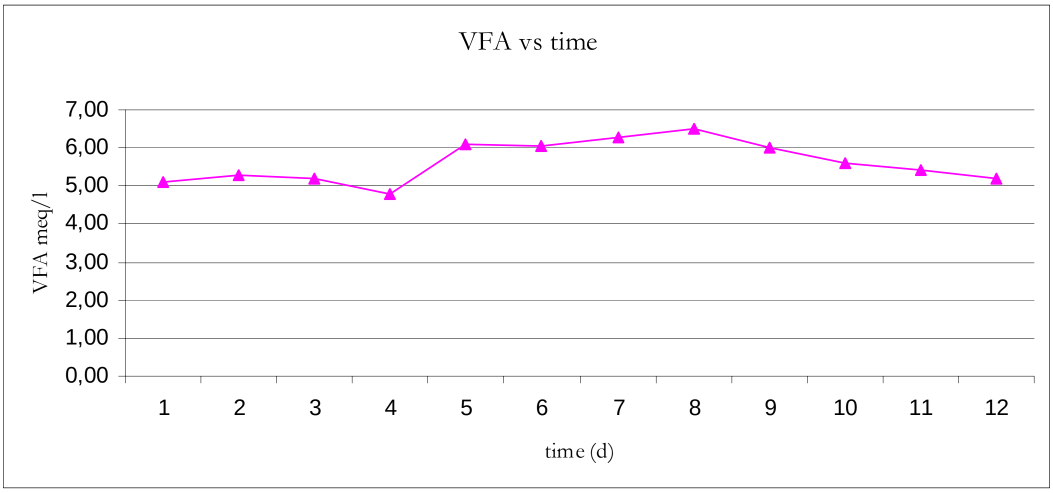

Figure 4.4 VFA vs. time, OLR = 5.3 kg VS / m^3.d (▲) .

Comparing the biogas production rate, and biogas yield with Experiment I of OLR=3.3 kg VS / m^3.d; both have been found to be higher than that of Experiment I's data. Corresponding VFA concentrations for Experiment I and II are given in Figure 4.3 and Figure 4.4 respectively.

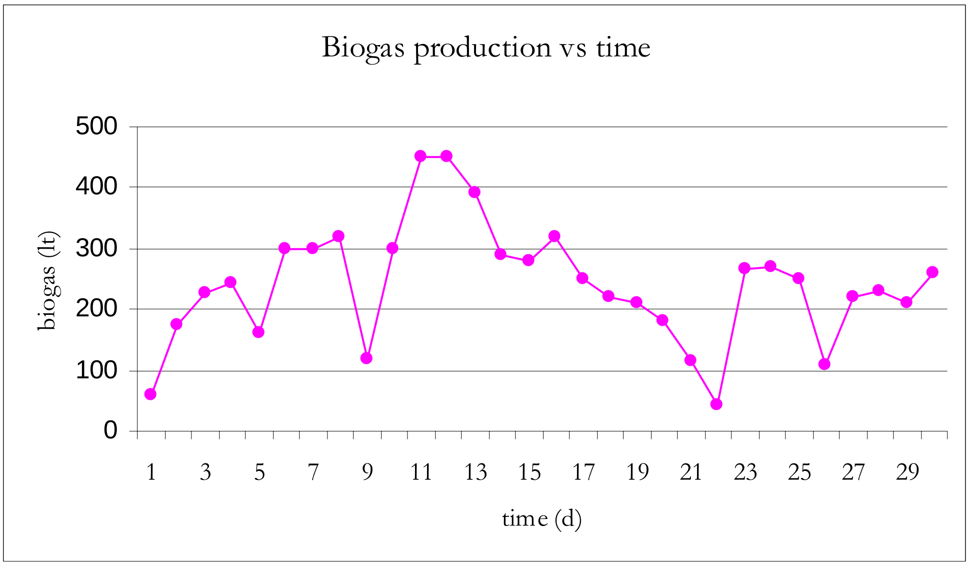

Figure 4.5 Daily biogas produced vs. time, OLR = 6.4 kg VS / m^3.d (●)

Since an increase in biogas production rate with the increasing OLR was observed, further increase in OLR was tested in Experiment III, with a new reactor (R2) as defined in Section 3.1. A new reactor was constructed, since the leakage in R1 could not be prevented. An OLR of 6.4 kg VS / m^3.d was fed to the reactor for this experiment. This value is higher than the limit value of 6 kg VS / m^3.d, which is stated in the experiment made by Mata-Alvarez (1992) with a mesophilic one-stage completely stirred reactor for the treatment of the organic fraction of the wastes coming from a large food market. The biogas production rate and biogas yield at this OLR averaged 246 L/day and 0.2 L / g VS added, respectively. Similar to the situation in Experiment I, the biogas production peaked on day 11, with a value reaching 450 L/d (Figure 4.5).

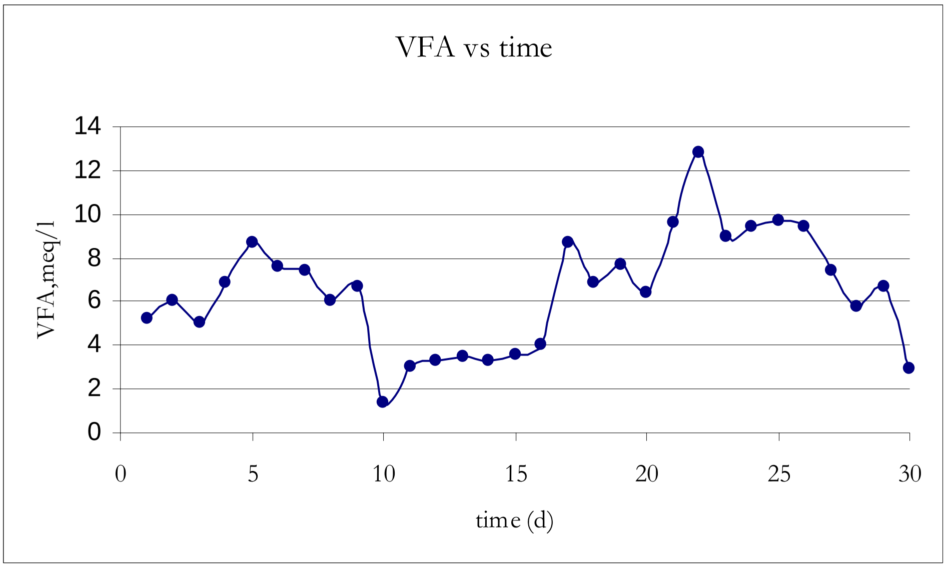

Figure 4.6 VFA vs. time, OLR = 6. 4 kg VS / m^3.d (●)

Though the biogas production rate increased; there has been a sharp decrease in biogas yield; compared to previous experiments. One cause of failure of the reactors could have been hydraulic overload causing a wash-out of the microorganisms. Another cause could be organic overload, where the inhibition of the micro-organisms was caused by the accumulation of VFAs, and due to the low buffering capacity in the digester liquid pH decreased, causing further inhibition (Mata-Alvarez et al., 1992; Murto et al., 2004). It was concluded that this problem should have arisen from the latter, since there was no possibility for a hydraulic wash-out since HRT was not altered; so as to cause a wash-out of microorganisms. In addition to this, higher VFA concentrations were observed compared with Experiments I and II. The VFA concentrations averaged 4; 6; and 7 meq/L as acetic acid for Experiments I, II and III respectively. The VFAs were stable all through the experiment for I and II as can be concluded from Figures 4.3 and 4.4; whereas it fluctuated within the range of 2 – 13 meq / L for Experiment III. NaOH was added (5 ml NaOH / ml raw waste) to the reactor on day 22 to decrease the pH value.

To sum up; biogas yields for OLRs of 3.3 , 5.3 and 6.4 kg VS / m^3.d were found to be 0.396 L / g VS ; 0.431 L / g and 0.2 L / g VS added respectively. The final increase in OLR caused digester failure.

Reviewing the literature, Gunaseelan (1997) reported a methane yield of 0.42 CH_4 m^3/ kg VS for potato waste. Gunaseelan (2007) also obtained the methane yields of 0.29–0.40 L/ g VS added for different fruit and vegetable solid waste. Parawira (2004) reported a biogas yield of 0.32 L CH_4/g VS degraded in a single fermentation process when a mixture of potato and sugar beet leaves was used as substrates. Zhu et al. (2008) experimented anaerobic digestion of potato waste using a two-stage AD process and the corresponding methane yield was 0.387 L/g VS added. Bouallagui et al. (2005) concluded that the methane yields from FVW ranged in 0.16 to 0.4 m^3 /kg VS added.

Callaghan et al. (2002) examined the co-digestion of FVW with cattle slurry and chicken manure. The methane yields they obtained was 0.35–0.4 L g VS added are similar to the in the current study for snacks waste and sludge co-digestion.

Studies of Alvarez and Lidén (2008); Dinsdale et al. (2000) and; Kaparaju et al. (2005) also resulted in biogas yields ranging from 0.3 to 0.37 kg VS /m^3. d for anaerobic digestion of similar kind of waste.

In order to compare biogas production rates with the theoretical data; biogas production rates based on waste composition and biogas production rates based on COD removal (Appendix B) were calculated and overall results are summarized in Table 4.1.

Table 4.1 Theoretical versus Experimental Biogas Production Rates

OLR, kg VS / m^3.d	Theoretical biogas production rate based on waste composition, L/d	Theoretical biogas production rate based on COD removal , L/d	Experimental biogas production rate, L/d
3.3	78	182	114
5.3	141	109	207
6.4	305	274	246

Table 4.1 identifies that biogas production rate for OLR 3.3 kg VS / m^3.d is higher than theoretical value calculated regarding waste composition; and lower than theoretical value calculated regarding COD removal.

Biogas production rate for OLR 5.3 kg VS / m^3.d is higher than both the theoretical value calculated regarding waste composition; and the value calculated regarding COD removal.

Biogas production rate for OLR 6.4 kg VS / m^3.d is lower than both the theoretical value calculated regarding waste composition; and the value calculated regarding COD removal. Cause of this situation might be inhibition of the micro-organisms that was caused by the accumulation of VFA; so that thorough decomposition of organic matter could not be achieved.

The experimental study showed that the biogas yield generated by co-digestion of snacks production plant wastewater sludge and organic waste, 0.431 L / g VS added achieved at an OLR of 5.3 kg VS / m^3.d, is higher than any of the values obtained for yields from similar FVW or food waste co-digestion. One reason for these high values achieved can be because of the buffering capacity of anaerobic sludge, that eases biomethanation of highly biodegradable organic waste. This shows that the organic waste from a snacks production facility is an excellent by-product that can be co-digested within the plant.

4.1.2 COD removal

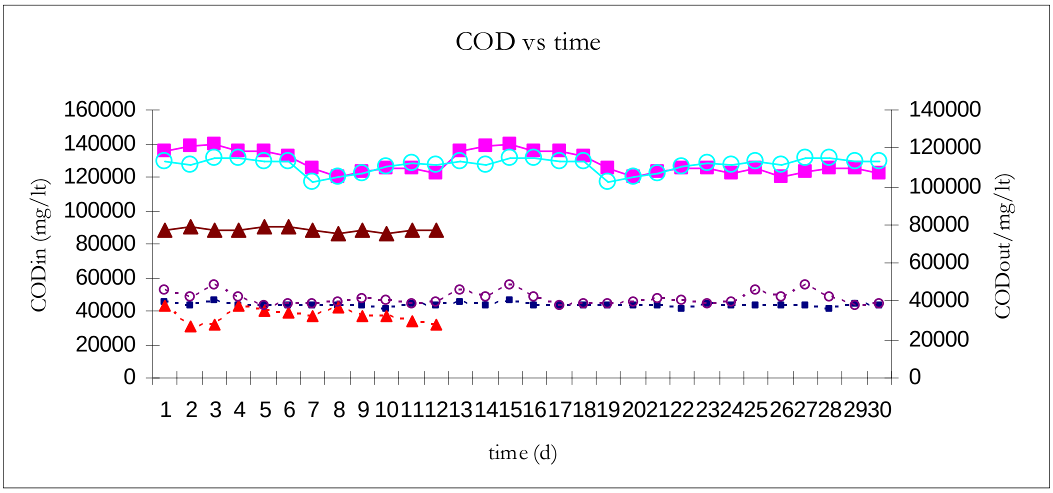

Figure 4.7 COD removal rates for OLR = 3.3 kg VS / m^3.d (■) , 5.3 kg VS / m^3.d (▲) 6.4 kg VS / m^3.d (○) COD $_{in}$ (__) COD_{out} (---)

COD removal ranged from 64% -67%; with the highest efficiency obtained for OLR 3.3 kg VS /m^3.d . COD values observed at the substrate and within the reactor are depicted as COD_{in} and COD_{out} in Figure 4.7. COD is a good indicator of the degree of completeness of the degradation process, as any undigested material will require oxygen (in an aerobic environment) to complete degradation (Ward et al., 2008). Higher COD removal rates point out the higer completeness of the process.

According to a study; where Zhu et al. (2008) co-digested potato waste using a two-stage anaerobic digestion process; 70% of VS, 64% of total COD in the feedstock were removed.

Senturk et al. (2009) found out that COD removal efficiencies of thermophilic anaerobic contact reactors treating food industry wastewater at a potato processing plant were 86–97%.

H. Bouallagui et al. (2004) used a two-phase anaerobic digestion system to treat fruit and vegetable wastes and overall COD removal in the treatment system was 96%.

These values are lower than these cited studied; meaning that there might be further opportunities to increase the biogas production rate through further degradation.

4.1.3 VS removal

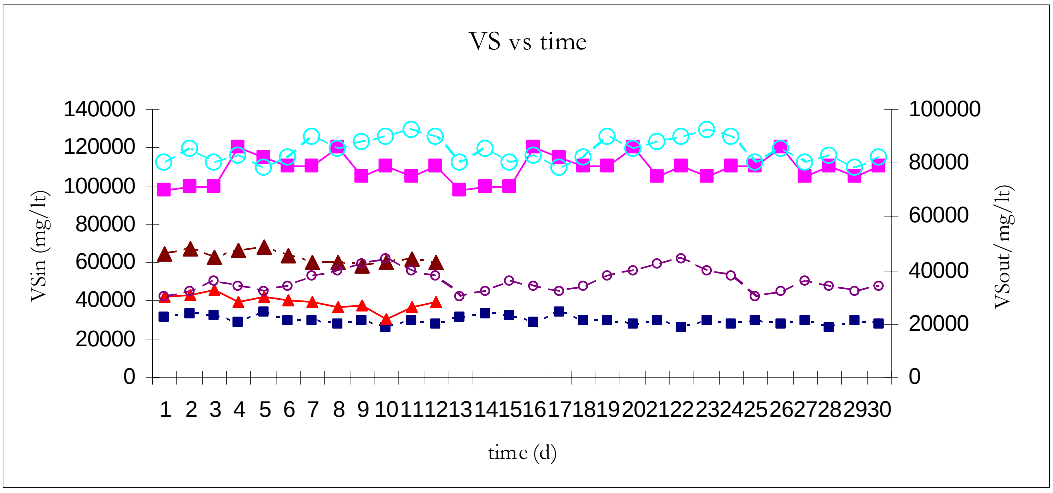

Figure 4.8 VS removal rates for OLR = 3.3 kg VS / m^3.d (■), 5.3 kg VS / m^3.d (▲) and 6.4 kg VS / m^3.d (○) VS_{in} (__) VS_{out} (---)

Average VS removal had been 60%, with the values ranging between 56-69% (Figure 4.8). The highest value was obtained for OLR 3.3 kg VS/ m^3.d. The volatile solids removal rate was compatible with the outcome of COD removal, where the highest removal was achieved at the lowest OLR. The inlet COD and VS was almost the same throughout a week, since the same substrate was being stocked and used for feeding the reactors. The lowest value, among the OLRs tested gave the highest VS removal efficiency; meaning that the maximum organic utilization occured at the lowest OLR. However, since the organics available were still less than the organics utilization capacity of the bacterial culture within the reactor; the OLR of 5.3 kg VS/ m^3.d resulted in a higher biogas yield.

4.1.4 pH

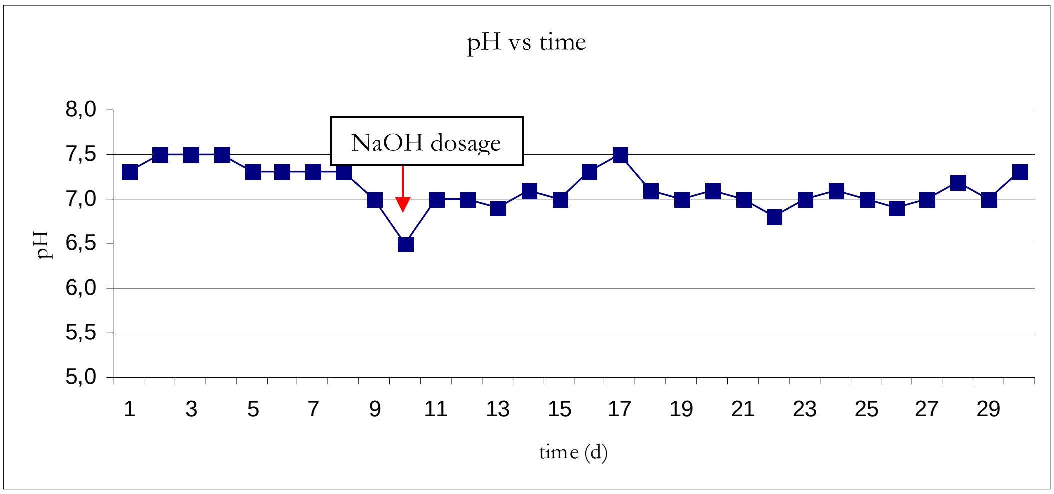

Figure 4.9 pH vs. time, OLR = 3.3 kg VS / m^3.d (■)

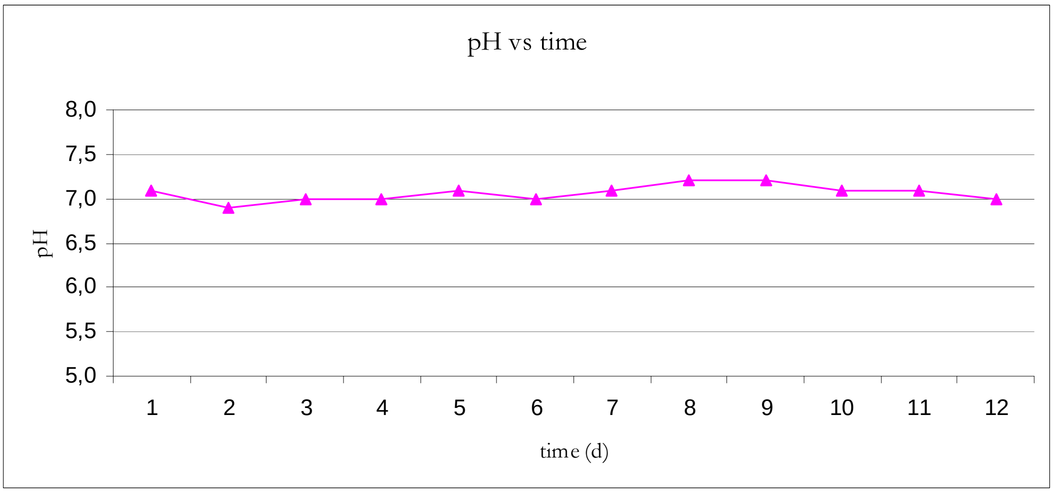

Figure 4.10 pH vs. time, OLR = 5.3 kg VS / m^3.d (▲)

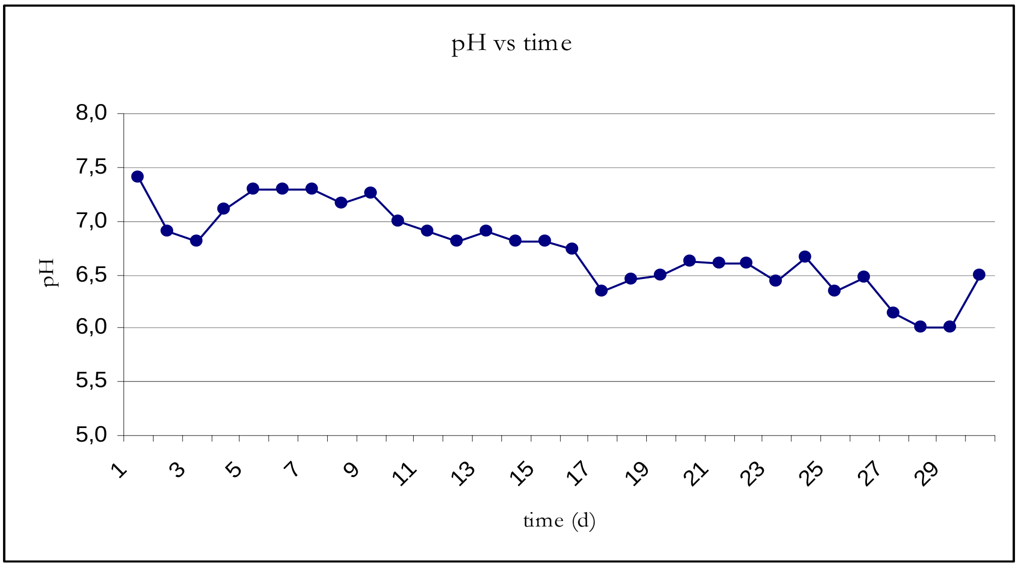

Figure 4.11 pH vs time, OLR 6.4 kg VS /m^3.d (●)

No inhibition effects observed during the experiments; and the lowest pH value was observed to be 6.5 in Experiment I; which was elevated to 7 with the addition of 5 ml NaOH / ml raw waste. (Figures 4.9, 4.10, and 4.11). Also pH value tended to fluctuate after day 16 in Experiment III, where a problem with the mixer was encountered. NaOH addition (5 ml NaOH / ml raw waste) was made, however the value remained in the range of 6.5-6.7 without causing any disruption in biogas formation. Keeping in mind that the ideal pH range for anaerobic digestion is very narrow; being between 6.8 and 7.2; and the growth rate of methanogens is greatly reduced below pH 6.6 (Mosey and Fernandes, 1989); the reactors were operating under optimal conditions for methane production .

The case was as Murto et al. (2004) summarized in their work of co-digestion of sewage sludge and potato processing industrial waste. They concluded that the pH values were 6.8–7.0 in all reactors experimented during stable operation. The stable pH was a result of modified inoculum to feed ratio as Gunaseelan (1995) suggested, along with the buffering effect of anaerobic sludge.

VFA monitoring was suggested by Ahring et al. (1995), since it has been demonstrated to indicate process stability, as an increase in fatty acids could be indicative of an overload of the organic loading rate. All the experiments were conducted through VFA control (feeding realized if VFA < 5 meq/L ; 75 mg/L as acetic acid), and this might be another reason that reactor upset has not been experienced..

For the third experiment with OLR = 6.4 kg VS /m^3.d; pH could not be kept constant, though stable conditions for pH were achieved in Experiments I and II (Figures 4.7 and 4.8). During 57% of the period for which the experiment was being conducted; the pH values were in the range of 6.5 – 7.0 ; and for 20% of the period it was in the range of 6.0 – 6.5. VFA concentrations were above 5 meq / L for 70% of the time; and pH was tried to be kept constant with NaOH dosage. However, VFA concentration increased up to 13 meq/L on day 22 and reactor pH could not be controlled, leading to inhibition of biogas production.

4.1.5 Nutrients (phosphorus and nitrogen)

Total Phosphorus removal has been 51 - 64%, whereas Total Nitrogen remained almost the same, with 0.6- 0.7 % removal. (Tables 4.2 and 4.3). This can be attributed to the anaerobic conversion of proteins contained in organic waste into amino acids, and then to ammonia (Demirer and Chen, 2005) . Removed phosphours is thought to be used as the nutrient for biosynthesis; and eventually for build-up of new bacterial cells (Khanal, 2008)

Table 4.2 Total nitrogen removal

OLR (kg VS / m^3.d)	**N_{in} (mg/L)**	**N_{out} (mg/L)**	**N removal (%)**
3.3	1328	1319	0.7
5.3	1490	1480	0.7
6.4	1560	1552	0.6

Table 4.3 Total phosphorus removal

OLR (kg VS / m^3.d)	P_{in} (mg/L)	P_{out} (mg/L)	P removal (%)
3.3	39	14	64
5.3	35	17	51
6.4	32	15	53

4.1.6 Biogas composition

Methane content of the gas averaged 67 % in all experiments, with the highest percentage achieved at day 14 of Experiment I to be 75%. (Tables 4.4-4.5-4.6). The gas composition remained almost in the same range even when the OLR was increased.This situation is in line with Murto's (2004) studies.

Senturk et al., (2009) asserted that the gas composition produced mainly depends on the nature of substrates. Since the substrate remains the same, the outcome was as expected.

Average methane content for the type of sludge and waste co-digested can be calculated from Khanal's work of theoretical methane percentages for different waste streams (2008), and it gives us the value of 65%. The methane content of the gas is, thus, higher than the theoretical value.

To the best of our knowledge, co-digestion of waste from snacks industry (organic waste and wwtp sludge) has been examined for the first time in the literature; and as a result of biogas yield, and corresponding methane content, it can be concluded that this process can successfully be applied in snacks plants.

Table 4.4 Biogas composition, OLR = 3. 3 kg VS / m^3.d

Parameter	Unit	Measurement 1	Measurement 2
CH_4 content	%	75	65
H_2S content	ppm	100	80

Table 4.5 Biogas Composition Table, OLR = 5.3 kg VS / m^3.d

Parameter	Unit	Measurement 1
CH_4 content	%	67
H_2S content	Ppm	90

Table 4.6 Biogas composition, OLR = 6.4 kg VS / m^3.d

Parameter	Unit	Measurement 1	Measurement 2
CH_4 content	%	67	64
H_2S content	ppm	85	80

Table 4.7 summarizes the COD, VS, TN, TP removal efficiencies and methane content of biogas produced for Experiments I, II and III. OLR of 3.3 kg VS / m^3.d had the highest VS, COD, phosphorus removal efficiency and the highest methane content; however OLR of 5.3 kg VS / m^3.d produced the highest biogas yield. Though the OLR of 6.4 kg VS / m^3.d efficiently removed COD and VS, it caused inhibition of methanogenic bacteria leading to an increase in VFA concentration and correspondingly a decrease in biogas yield.

Table 4.7 Summary of Experiment Efficiencies I-II and III

Organic Loading Rate (kg VS/m^3d)	VS in the feed (%)	HRT (days)	Percent removals, %				Average Methane content of biogas (%)
			COD	VS	TN	TP	
3.3	6.4	30	67	69	0.7	64	70
5.3	16	30	63	56	0.7	51	67
6.4	9.5	30	64	59	0.6	53	65

4.2 Performance assessment of anaerobic co-digestion facility (ACF)

This part of the study covered the performance assessment of currently operating anaerobic co-digestion facility (ACF), that consisted of two digesters having volumes of 1200 m^3 and 3000 m^3 each .

Biogas production, energy production and methane content of produced biogas were reviewed, to start with. Theoretical data was compared with actual values of ACF's biogas and energy production and assessed accordingly. Secondly, operational parameters were discussed; mainly focusing on organic waste admission and corresponding OLRs. ACF's daily OLR data was investigated and compared with the data obtained from the experiment results given in Section 4.1. Lastly, greenhouse gas emissions reduced both by the operation of ACF; and resulted from the adjustments made within the scope of this study was calculated; and commented on.

4.2.1 Biogas production

Biogas production rate and corresponding methane content of biogas was taken as the performance parameters for the ACF.

Biogas production potential for the average substrate mixture loaded to the ACF would be 37 m^3 biogas / ton of waste as calculated in Appendix A. Setting out the actual waste quantities fed into ACF; and theoretical and actual biogas production rates; biogas production efficiency of ACF can be calculated as in Table 4.8:

Table 4.8 ACF performance parameters

Parameter	**Total**
Total mixed waste quantity ,actual (ton/yr) = (A)	43,800
Annual biogas production, theoretical, (m^3/yr) = (A)*37 m^3 / ton = (B)	1,780,000
Annual biogas production ,actual, (m^3/yr) = (Measured) = (C)	2,800,000
Actual yield vs. theoretical yield, (%) = (C) / (D)	157

Since methane content of biogas delivers its quality; it can not be said that biogas production efficiency of ACF was 157%. Actual methane content should be considered in order to correct the efficiency data. Table 4.9 shows the actual methane content versus the theoretical methane content; which were the same. Hence, the value calculated with Table 4.8 was the actual biogas production efficiency for ACF (Table 4.9)

Table 4.9 Average Methane Content of Biogas

Parameter	**1st Stage**	**2nd Stage**
Methane content, actual, (%)	65	65
Methane content, theoretical, (%)	60-65	60-65
Actual vs. theoretical methane content	100	100

Table 4.10 ACF performance corrected for methane content

Parameter	Total
Annual biogas production, theoretical, (m^3/yr)	1,780,000
Annual biogas production, actual, (m^3/yr) (A)	2,800,000
Actual vs. theoretical methane content (B)	100
Biogas production corrected for actual methane content, (C) = (A)* (B), (m^3/yr)	2,800,000
Actual yield vs. Theoretical yield, (C) / (A), (%)	157

4.2.2 Energy Production

Heat and electrical energy is produced via utilization of produced biohgas in microturbine, gas engine and boilers. Corresponding total energy produced from the ACF in the different co-generation systems (CHP's) are provided in Appendix C; and related heat and electricity consumptions were tabulated and provided in Table 4.11 below:

Table 4.11 Annual Energy Production

Parameter	Energy Produced Total
Annual biogas production (m^3/yr)	2,800,000
CHP – micro turbine (kWe)	65
CHP – engine installed power (kWe)	330
Total electrical energy produced (kWh/yr)	3,460,200
Total heat energy produced (kWh/yr)	3,229,155
ACF heat consumption (kWh/yr)	1,401,600
ACF electrical consumption (kWh/yr)	525,600
Net electrical gain (kWh/yr)	2,934,600
Net thermal gain (kWh/yr)	1,827,555

4.2.3 OLR effects

The performance of ACF was determined to be 157% higher than both the design values, and the literature values. This made sense since the facility was one of the firsts in its kind; and the design was made with the notion of being on the safe side. Hence, many areas of improvement still existed, mainly for adjusting an optimum OLR :

- Sustaining a consistent and higher daily OLR
- Intake of more organic waste to the ACF
- Continuous organic waste feeding

Organic waste admission to the ACF and OLR effects

The 4200 m^3 reactor had a capacity of co-digesting 30,000 tons/yr of organic waste, however approximately 19,500 tons was fed in year 2009, due to startup conditions. The actual amount of organic waste generated, however not utilized in the ACF accounts for 2100 tons (Table 4.12), that would have generated 566,000 m^3 biogas. Types and amounts of organic waste actually fed to the ACF can be found in Table 4.12 below. Correspondingly, organic waste left out is provided in Table 4.13

Table 4.12 Organic waste admitted to ACF (2009)

Month	WWTP sludge (m^3)	Potato mesh (ton)	Potato pieces (ton)	Corn (ton)	Scrap product (ton)	Starch (ton)	Grass (ton)	Raw material waste (ton)
Jan.09	1,269	231						
Feb.09	680	230			6			
Mar.09	507	227		2				
Apr.09	600	259	35		24		0.4	
May.09	861	266			7		0.3	
June.09	1,002	133	3		12		0.3	
July.09	2,317	61			0.7		0.3	
Aug.09	2,015	213			16	43	0.2	
Sep.09	1,691	287			11	70	0.2	7
Oct.09	1,679	344			14	317		26
Nov.09	1,504	291			27	0		6
Dec.09	1,943	318			26	52		
Total	16,068	2.858	38	2	144	483	1.7	39

Table 4.13 Organic waste not admitted to ACF (2009)

Month	Product scrap (ton)	Chips (ton)	Potatoes (ton)	Depot potato (ton)	Starch (ton)	Corn (ton)	Seasoning (ton)
Jan.09	47		67		39	3	
Feb.09	35		62		46	4	0,8
Mar.09	37		36	75	61	3	1
Apr.09	23		118	75	73	3	4
May.09	12	4	68	20	62	7	
June.09	13	6	111		48	6	
July.09	21	10	147		17	10	
Aug.09	29	7	108		14	8	
Sep.09	16	11	84			6	
Oct.09	27	2	50		63	4	
Nov.09	15	11	45		82	2	
Dec.09	23	3	49		31	1	
Total	**297**	**53**	**943**	**170**	**534**	**58**	**5,8**

Investigating the waste streams and intakes; all the organic waste generated, which accounted for 2000 tons /month was added to the loading recipe of ACF, as per the outcome of this study. The value of 2000 tons /month is obtained by addition of annual amount that was not admitted to ACF, as defined in Table 4.13.

Experiments conducted with the experimental set-up showed that the maximum biogas yield was achieved at an OLR of 5.3 kg VS / m^3.d. This showed that the ACF had extra capacity, which could be utilised. Provided that the laboratory-scale results were applicable to the ACF, and that the system was run either with the two reactors in parallel or with the material completely mixed by recirculation, the present organic load could be increased at least twofold. This finding also supports the work of Ward et al. (2008), which stated that many of the anaerobic digesters were simple in design and run well below their potential organic loading rate to prevent overloading which can cause digester failure. The typical OLR scheme of ACF is provided in Figure 4.12. The dashed line shows the design OLR of the ACF; and the straight line is the OLR that resulted in the highest biogas yield through experimentation.

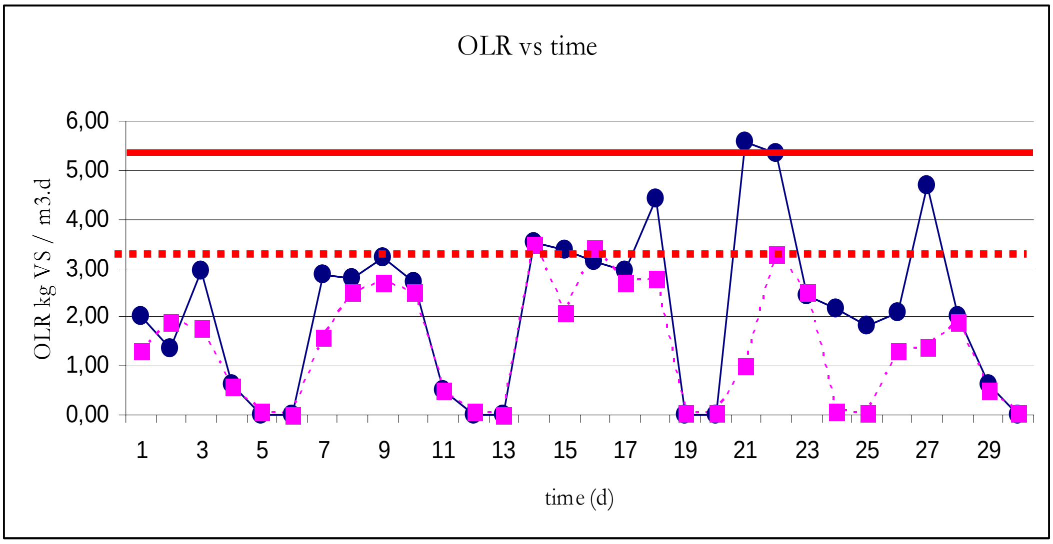

Figure 4.12 Daily OLR variations for the ACF ; 1200 m^3 reactor (●); 3000 m^3 reactor (■) Design OLR value ············ Maximum value obtained by experiments ———

As can be concluded from Figure 4.12; OLR was highly fluctuating through the course of a month. This was because of the dependancy of ACF loading on snacks production schedule. Since the production activities generally lasted four days a week; the ACF was fed with organic waste during those four days and was only fed with anaerobic sludge for the remaining three days. In order to overcome this fluctuating regime; and to increase the OLR; a seven-day-loading-schedule was set-up, by reviewing the manufacturing plan every Monday and the presuming the waste generated was divided equally for each day of the week. A stock area has been constructed; so that the organic waste was collected in the area to be fed to the system during the weekend. Resulting daily OLR distribution was determined to be as depicted in Figure 4.13.

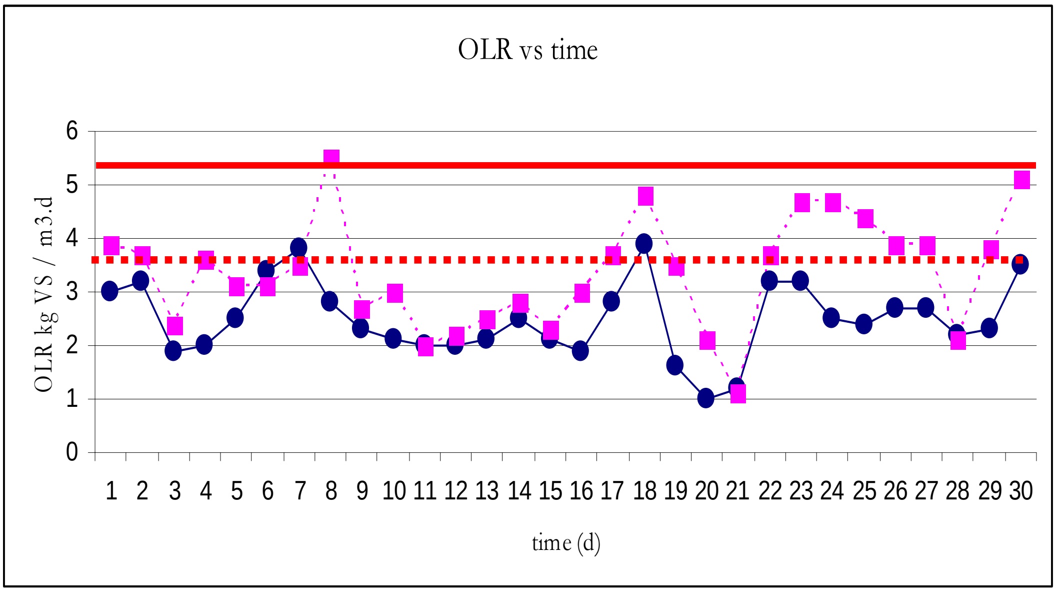

Figure 4.13 Daily OLR variations for the ACF after reorganizing the loading schedule; 1200 m^3 reactor (●); 3000 m^3 reactor (■) Design OLR value·············· Maximum value obtained by experiments———

Overall increase in monthly biogas production achieved by the adjustments made in the loading regime and increase in the OLR from 1.8 kg VS / m^3.d to 3 kg VS / m^3.d was 60,000 m^3 of biogas for the 3 months that the measures have been taken. The average of 120,000 m^3/month biogas generation increased to 180,000 m^3/month biogas generation. This meant 50% net increase in biogas generation. Related graph is depicted below (Figure 4.14)

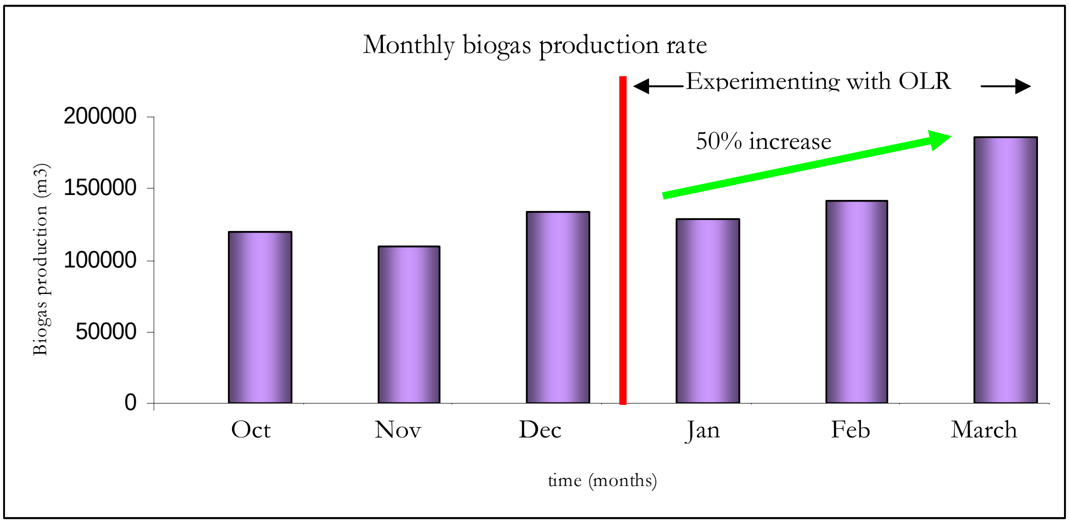

Figure 4.14 Monthly biogas production rate (October 09- March 10)

4.2.4 Greenhouse effects

Biogas generated was utilized in the gas engine, microturbine; and the boilers. The flare was used if there was excess energy produced. The energy utilization hierarchy was utilizing the gas in the gas engine first (330 kW); then in WWTP boilers; then in microturbine (65 kW) and the least preferred option was flaring. Compliance to this hierarchy was important since the more the biogas was utilized; the less would be the greenhouse gas emissions generated. The aim was utilizing the maximum amount of energy that was produced.

The ACF was generating 3.5 million kW /yr of total energy (electricity); of which 0.5 million kW /yr was supplied to ACF energy needs. The ACF was a net zero energy plant. Energy production and consumption values are provided in Appendix C. In below Figure 4.15; daily values of total biogas generation versus total biogas utilization was supplied; for the period January-March 2010. The Figure proves that the biogas production rate increase 50%; whereas the utilization rate increased 13%.

Enhancing the biogas production by 50% as declared in Section 4.2.3; meant that an additional saving of 1,530,250 m^3 of greenhouse gas as CO_2 would annualy be achieved. This calculation is based on the assumption that each kwh electricity usage results in 0.462 kg of CO_2 generation (Defra, 2007); and density of CO_2 being 0.717 kg/m^3. Related calculations are shown in Table 4.14.

Table 4.14. Greenhouse gas emission saving

Base case	Unit	Parameter	Equation	Value
Net green energy	kWh/yr	A		4,762,155
GHG from electricity usage (CO_2)	kg / yr	B	A*0.462	2,200,116
GHG from electricity usage (CO_2)	m^3/yr	C	B/0.717 kg/m^3	3,068,502
Improved case (50% increase in biogas)	Unit			Value
Net green energy	kWh/yr	D		7,143,233
GHG from electricity usage (CO_2)	ton / yr	E	D*0.462	3,300,173
GHG from electricity usage (CO_2)	m^3/yr	F	E/0.717 kg/m^3	4,602,752
GHG saving	**m^3/yr**	**G**	**F-C**	**1,534,250**

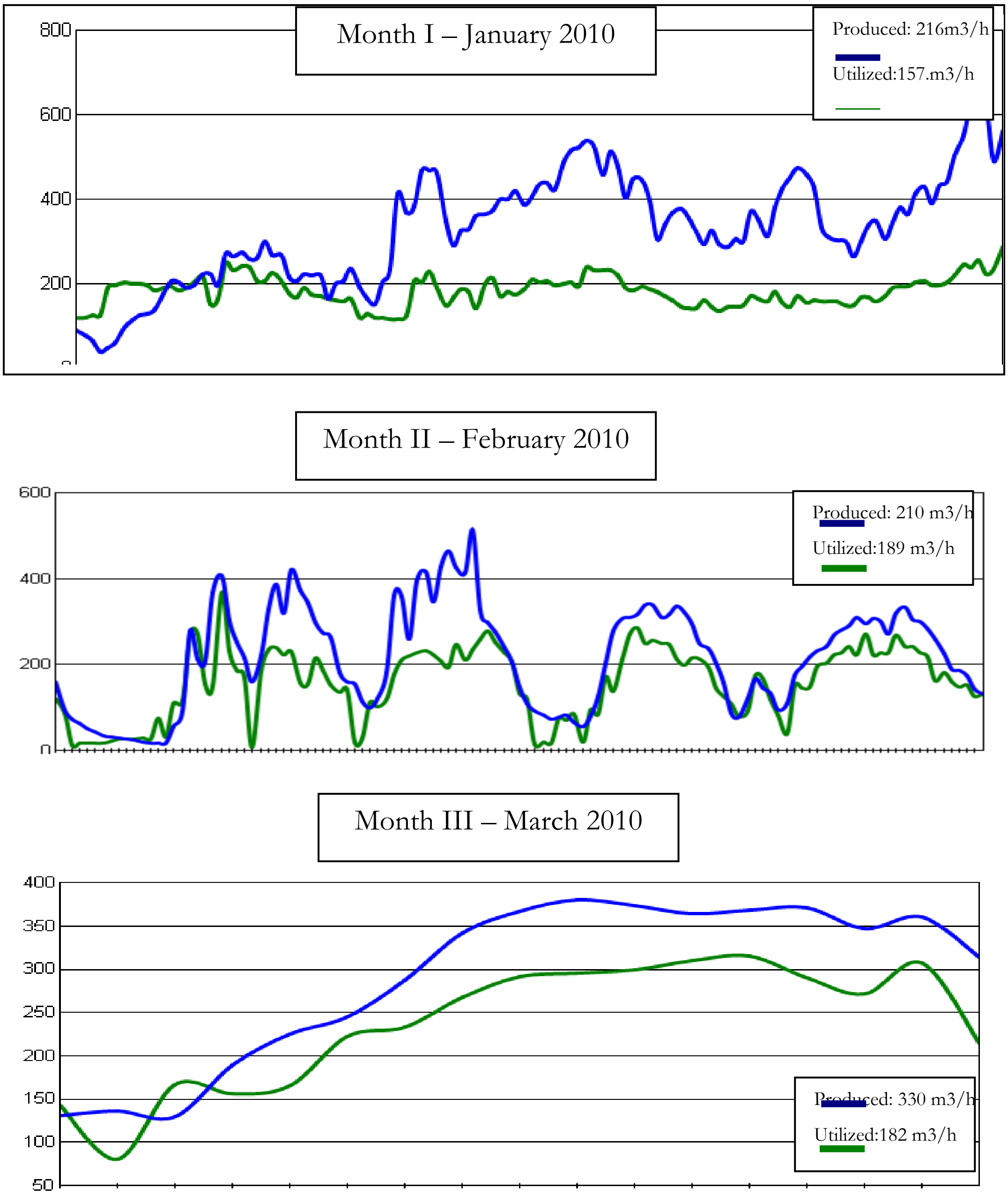

Figure 4.15 Biogas generation vs utilization (Jan-Mar 10)

CHAPTER 5

CONCLUSIONS

Even though anaerobic digestion of organic waste and wastewater sludge are popular and well-known issues; opportunities for practical industrial applications of these are not fully exploited to the time. Snacks production is one of these industries where organic waste generation is very high, along with their recycling rates. The product and raw material waste serves as animal feed, whereas sludge cake from the WWTP is used as soil conditioner. However, chances are high that demand from these recycling markets (such as farmers and cattle owners) might not meet the supply from the plant, especially in hot seasons. This valuable waste then is under threat of becoming a problem for environmental and public health; such as causing odor and insect problems. Moreover, degredation products of these waste is one of the major contibutors to greenhouse effect.

In recognition of all these facts, the main objective of this study was to enhance biogas production of the ACF. Two routes were followed for this purpose; first being the investigation of OLR effects in an experimental set-up; and second being the assessment of ACF's biogas production performance through observation of biogas production rate, and OLR . Results obtained from the experiments conducted were used to improve ACF's OLR regime.

Based on this study, the following conclusions could be drawn from each of the studies:

OLR experiments with the experimental set-up

- Three different organic loading rates; namely 3.3; 5.3 and 6.4 kg VS / m^3.d were applied to the experimental set-up; and it was observed that the OLR of 5.3 kg VS/m^3 yielded the highest biogas generation rate and biogas yield.
- Biogas yield decreased drastically for OLR of 6.4 kg VS/m^3.
- The single-phase conventional AD process for co-digestion of organic waste and anaerobic sludge is sensitive for Organic Loading Rate changes, since differing the OLR from 5.3 to 6.4 kg VS / m^3.d gave a sharp decrease in biogas yield.
- The highest COD and VS removal were achieved with OLR of 3.3 kg VS/m^3.d
- The process did not remove TKN, which was expected. Organic Nitrogen was converted into ammonia nitrogen.

Assessment of ACF and OLR effects

- AD process was a highly feasible option for snacks production industry to utilize their organic waste and convert waste into energy. A reactor of 4200 m^3 could digest the total organic waste of a plant with 30,000 ton/yr production capacity; and generate 3,460,200 kwh/yr of electrical energy.
- 10% of organic waste produced was not being admitted to the ACF.
- 50% increase in biogas production of ACF was obtained via increasing the OLR from 1.8 kg VS / m^3. d to 3 kg VS / m^3. d and applying a continuous organic waste loading regime.
- 50% increase yielded in a greenhouse gas saving of 120,000 m^3 / month, that would result in a greenhouse gas saving of annually 1,530,250 m^3.
- It was not possible to apply the OLR of 5.3 kg VS / m^3. d ; that gave the highest biogas yield during the laboratory scale experiments; since organic waste generated was the limiting factor.

Recommendations

Recommendations for future work on the ACF would be:

- Consideration of two-phase configuration option;
- Optimization and building a consistent recipe for loading;
- Optimization for sludge feed ;
- Strict observation of operational parameters such as VFA and COD within the reactor; and investigation of mixing conditions; and
- Addition of ingredients with high biogas potential such as grease trap sludge or energy crops.

REFERENCES

American Public Health Association (APHA) (2005). "Standard Methods for the Examination of Water and Wastewater", 21st ed., Washington D.C., USA.

Ahring, B.K., Sandberg, M. and Angelidaki, I. (1995). "Volatile fatty acids as indicators of process imbalance in anaerobic digesters." *Applied Microbiology and Biotechnology,* 43, 559-565.

Alkaya, E. (2008). "Biorefining of sugar-beet processing wastes by anaerobic biotechnology; Waste stabilization and bioproduct formation." MSc Thesis, Middle East Technical University , 1-130

Alvarez, R. and Lidén, G. (2008). "Semi-continuous co-digestion of solid slaughterhouse waste, manure and fruit and vegetable waste." *Renewable Energy*, 33, 726-734

Angelidaki, I. and Ellegaard L. (2003). "Codigestion of manure and organic wastes in centralized biogas plants." *Applied Biochemistry and Biotechnology*, 109, 95-105.

Appels, L., Baeyens, J., Degreve, J. and Dewil, R. (2008). "Principles and potential of the anaerobic digestion of waste-activated sludge." *Progress in energy and combustion science*, 34, 755-781

Ayalon, O., Avnimelech, Y., and Shechter, M. (2001). "Solid waste treatment as a high-priority and low cost alternative for greenhouse gas mitigation." *Environmental Management,* 27, 697-704.

Babel , S., Sae-Tang, J., and Pecharaply, A. (2009). "Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application." *International Journal Environmental Science Technology*, 6 (1), 131-140.

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders,W.T.M., Siegrist, H. and Vavilin, V.A. (2002). " The IWA Anaerobic Digestion Model." *Water Science and Technology*, 45, 65-73.

Bitton, G. (1994). Wastewater Microbiology, 1st ed., Wiley-Liss Inc., New York

Bolzonella, D., Battistoni, P., Susini, C. and Cecchi, F. (2006). "Anaerobic codigestion of waste activated sludge and OFMSW: the experiences of Viareggio and Treviso plants (Italy)." *Water Science and Technology*, 53, 203–211.

Bouallagui, H., Torrijos, M., Godon, J.J, Moletta, R., Ben Cheikh, R., Touhami, Y., Delgenes, J.P. and Hamdi, M. (2004). "Two phase anaerobic digestion of fruit and vegetable wastes: bioreactors performance." *Biochemical Engineering Journal* , 21, 193-197.

Bouallagui, H., Cheikh, R.B., Marouuani, L. and Hamdi M. (2003). "Mesophilic biogas production from fruit and vegetable waste in tubular digester." *Bioresource Technology*, 86, 85-89.

Bouallagui, H., Touhami, Y., Ben Cheikh, R. and Hamdi, M. (2005). "Bioreactor performance in anaerobic digestion of fruit and vegetable wastes.", *Process Biochemistry,* 40, 989–995

Bouallagui, H., Lahdheb, H., Ben Romdan, E., Rachdi, B. and Hamdi M. (2009). "Improvement of fruit and vegetable waste anaerobic digestion performance and stability with co-substrates addition." *Journal of Environmental Management* ,90, 1844-1849

Bouallagui, H., Haouari, O., Touhami, Y., Ben Cheikh, R., Mourani, L. and Hamdi, M. (2004). " Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste." *Process Biochemistry*, 39, 2143–2148

British Biogen (1997). "Anaerobic digestion of farm and food processing residues – Good practice guidelines." *Tehnical Report*, London, UK

Brummeler, E.T. and Koster,I.W. (1990). "Enhancement of dry anaerobic batch digestion of the organic fraction of municipal solid waste by an aerobic pretreatment step." *Biological Wastes*, 3, 199-210

Callaghan, F.J., Wase, D.A.J., Thayanithy, K. and Forster, C.F. (1999). "Co-digestion of waste organic solids: batch studies." *Bioresource Technology*, 67, 117–122.

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

Carucci, G:, Carrasco, F., Trifoni, K., Majone, M. and Beccar, M. (2005). "Anaerobic Digestion of Food Industry Wastes:Effect of Codigestion on Methane Yield." *Journal of Environmental Engineering*, 131:7, 1037-1045

Catarino, J., Mendonca, E., Picado, A., Anselmo, A., Nobre Da Costa, J. and Partidario, P. (2007). "Getting value from wastewater: by-products recovery in a potato chips Industry." *Journal of Cleaner Production*, 15, 927-931

Cecchi, F., Pavan, P. and Mata-Alvarez, J. (1996). "Anaerobic co-digestion of sewage sludge: application to the macroalgae from the Venice lagoon." *Resources, Conservation and Recycling,* 17, 57-66.

Chae, K.J., Jang, A., Yim, S.K. and Kim, I.S. (2008). "The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure." *Bioresource Technology* ,99, 1–6.

Custodio, S.C, Tongco, E.O. and Tiangco, C.C. (2006). "Waste to Energy Project: Pineapple Processing Waste Biomethanation and Treatment Plant." *Promotion of Renewable Energy and Greenhouse Gas Abatement (Prega), Pre-Feasibility Study Report,* 1-76

Darlington, R. , Staikos, T. and Rahimifard, S. (2009). "Analytical methods for waste minimisation in the convenience food industry." *Waste Management*, 29, 1274–1281

Davidsson, A., Lovstedt, C., La Cour Jansen, J., Gruvberger, C. and Aspegren, H. (2008). "Co-digestion of grease trap sludge and sewage sludge." *Waste Management* , 28 , 986–992

Defra (2007). "Guidelines to Defra's Greenhouse Gas Conversion Factors for Company Reporting.", *Department for Environment,Food and Rural Affairs Technical Guidelines*, London, UK

Demirer, G.N. and Chen S. (2005). "Two phase anaerobic digestion of unscreened dairy manure." *Process Biochemistry.*, 40, 3542–3549

Demirer, G.N, Duran, M., Ergüder, T.H., Güven, E., Ugurlu, Ö. and Tezel, U. (2000)."Anaerobic treatability and biogas production potential studies of different agro-industrial wastewaters in Turkey." *Biodegradation*, 11, 401-405

Demirer G.N. and Chen, S. (2004). "Effect of retention time and organic loading rate on anaerobic acidification and biogasification of dairy manure." *Journal of Chemical Technology and Biotechnology*, 79, 1381–1387

Deublein and Steinhauser (2008). "Biogas from waste and renewable Resources: An Introduction." 1st ed, Wiley - VCH, Weinheim-Germany

Dinsdale, R.M , Premier, G.C, Hawkes, F.R. and Hawkes, D.L. (2000). "Two-stage anaerobic co-digestion of waste activated sludge and fruit/vegetable waste using inclined tubular digesters." *Bioresource Technology* ,72, 159-168

European Commission (1999). "Council Directive on the landfill of waste." 1999/31/EC

IEA Bioenergy (2001). "Systems and markets overview of anaerobic digestion." *Technical Report*, Oxforshire, UK

EPA Ireland (2005). "Anaerobic digestion: Benefits for waste management, agriculture, energy, and the environment." *Discussion Report* ., 1-123

European Union Commission (2006). "Renewable Energy Road Map." *Communication from the commission to the council and the European Parliament*, Brussels

Ferreira das Neves, L.M.G. (2009). "Anaerobic Co-Digestion Of Organic Wastes." *MSc Thesis, Universidade do Minho, Portugal*

Gavala, H.N., Skiadas, I.N., Bozinis, A.N. and Lyberatos, G. (1996). "Anaerobic co-digestion of agricultural industries' wastewaters." *Water Science and Technology,* 11, 67-75

Gijzen, H.J. (2002). "Anaerobic digestion for sustainable development: a natural approach." *Water Science and Technology*, 10, 321-328.

Gomez, X., Cuetos, M.J., Cara, J., Moran, A. and Garcıa, A.I. (2006). "Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes. Conditions for mixing and evaluation of the organic loading rate." *Renewable Energy*, 31, 2017–2024.

Gunaseelan, V.N. (1995). "Effect of inoculum substrate ratio and pretreatments on methane yield from Parthenium." *Biomass & Bioenergy* , 8 , 39–44.

Gunaseelan, V.N. (1997). "Anaerobic Digestion of biomass for methane production: A Review." *Biomass and Energy*, (13), 83-114

Gunaseelan, V.N. (2007). "Regression models of ultimate methane yields of fruits and vegetable solid wastes, sorghum and napiergrass on chemical composition." *Bioresour. Technologies*, 98, 1270–1277.

Hadjivassilis; I., Gajdos, S., Vavco, D. and Nicolauo, M. (1997). "Treatment of wastewater from the potato chips and snacks manufacturing industry." *Water Science and Technology*, 36, 329–335

Hendriks, A.T.W.M and Zeeman, G. (2009). " Pretreatments to enhance the digestibility of lignocellulosic biomass." Bioresource Technology ,100, 10- 18.

Hills, D.J. and Roberts, D.W. (1982). "Conversion of tomato, peach and honeydew solid waste into methane gas." *Transactions of the Asae* , 25, 820–826.

IPCC (1995). " IPCC guidelines for national greenhouse gas emission inventories, Reference manual, reporting guidelines, and Workbook.." *IPCC WGI Technical Support Unit, Hadley Center Meteorological Office*, Bracknell, UK.

IPCC (1996). "Climate change 1995: Impacts, adaptations and mitigation of climate change: Scientific–technical analyses." Cambridge University Press, Cambridge

Kaparaju, P. and Rintala, J. (2005). "Anaerobic co-digestion of potato tuber and its industrial by-products with pig manure." *Resources, Conservation and Recycling*, 43 , 175–188

Khanal,S.K. (2008). “Anaerobic biotechnology for bioenergy production.” 1st ed, Wiley-Blackwell, Iowa, U.S.A

Kizilkaya, R. and Bayrakli, B. (2005). “Effects of N-enriched sewage sludge on soil enzyme activities.” *Applied Soil Ecology*, 30, 192–202.

Knol, W., Vandermost, M.M. and Waart, J.D. (1978). “ Biogas production by anaerobic digestion of fruit and vegetable waste – preliminary study.” *Journal of the Science of Foodand Agriculture*, 29, 822–830.

Lane, A.G. (1979). “Methane from anaerobic digestion of fruit and vegetable processing waste.” *Food Technol Australia*, 31, 201–217.

Lettinga, G., A.F.M. van Velsen, S.W. Hobma, W. De Zeeuw, and A. Klapwijk. (1980). “Use of upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment.” *Biotechnology and bioengineering*, 22, 699-734

Mata-Alvarez, J. (2002). “Biomethanization of the Organic Fraction of Municipal Solid Wastes.” 1st ed, IWA Publishing, United Kingdom

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

Mata-Alvarez, J., Cecchi, F., Llabrés, P. and Pavan, P. (1992). “Anaerobic digestion of the Barcelona central food market organic wastes: plant design and feasibility study.” *Bioresource Technologies*, 42, 33–42

Mc Carty, P.L. (2001). “The development of anaerobic treatment and its future. " *Water Science and Technology*, 44 (8), 149-156.

Metcalf and Eddy, (2003). "Wastewater engineering, in: Treatment and Reuse." 4th ed., McGraw-Hill Higher Education, New York.

Montusiewicz, A., Lebiocka, M. and Pawlowska, M. (2008). "Characterization of the biomethanization process in selected waste mixtures." *Archives of Environmental protection ,* 3, 49- 61.

Mosey, F.E and Fernandes, X.A. (1989). "Patterns of hydrogen in biogas from the anaerobic digestion of milksugars." *Water Science and Technology*, 21, 187-196.

Murto, M., Björnsson, L. and Mattiasson, B. (2004). "Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure." *Journal of Environmental Management*, 70 , 101–107

Pain, B.F. and Hepherd, R.Q. (1985). "Anaerobic digestion of livestock wastes." *NIRD Technical Bulletins*, Reading :9-14.

Parawira, W. (2004). "Anaerobic Treatment of Agricultural Residues and Wastewater Application of High-Rate Reactors." Doctoral Thesis, Lund University, Sweden

Parawira, W., Read, J.S., Mattiasson, B. and Björnsson, L. (2008). "Energy production from agricultural residues: High methane yields in pilot-scale two-stage anaerobic digestion." *Biomass and bioenergy*, 32, 44-50

Pavan, P., Bolzonella, D., Battistoni, E. and Cecchi, F. (2007). "Anaerobic co-digestion of sludge with other organic wastes in small wastewater treatment plants: an economic considerations evaluation." *Water Science and Technology*, 56, 45- 53.

Rajeshwari, K. V., Balakrishnan, M., Kansal, A., Kusum, L., and Kishore, V. V. N. (2000). "State-of-the-art of anaerobic digestion technology for industrial wastewater treatment." *Renew. Sust. Energ. Rev.,* 4, 135–156.

Romano, R.T. and Zhang, R. (2008). "Co-digestion of onion juice and wastewater sludge using an anaerobic mixed biofilm reactor." *Bioresource Technology*, 99, 631-637.

Sawyer, C.N, McCarty, P.L. and Parkin, G.F. (2003). "Chemistry for Environmental Engineering and Science.", 5th ed., Mc-Graw-Hill Companies Inc., New York, U.S.A

Senturk, E., Ince, M. and Onkal, E., G. (2009). "Treatment efficiency and VFA composition of a thermophilic anaerobic contact reactor treating food industry wastewater." *Journal of Hazardous Material, doi:10.1016/j.jhazmat.2009.11.113*

Smet, E., Vanlangenhove, H. and Debo, I. (1999). " The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste." *Atmos. Environ*, 33 , 1295-1303.

Sosnowski, P., Wieczor, A. and Ledakowicz, S. (2003). "Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes." *Advances in environmental research*, 7, 609-616

Sosnowski, P., Smolka, A.K., Kaczorek, K. and Ledakowicz, S. (2008). " Kinetic investigations of methane co-fermentation of sewage sludge and organic fraction of municipal solid wastes. " *Bioresource Technology*, 99, 5731–5737

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

Tafdrup, S. (1995). "Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials." *Biomass and bioenergy*, 9, 303-314

Tchobanoglous, G., Burton F. L., and Stensel, H. D. (2003). "Wastewater engineering. treatment and reuse," 4th edition. McGraw-Hill Companies, New York, USA.

Titjen, C. (1975). "From Biodung to Biogas : Historical review of European Experience." *Energy, agriculture and waste management*, 347-359.

Torres, M.L. and Lloréns, M.C.E. (2008). "Effect of alkaline pretreatment on anaerobic digestion of solid wastes." *Waste management*, 28, 2229-2234

United States National Research Council (1995). "The role of technology in environmentally sustainable development." 1st ed., Council of academies and technological sciences,Sweden

Ward, A.J., Hobbs, P.J., Holliman, P.J. and Jones, D.L. (2008). "Optimisation of the anaerobic digestion of agricultural resources." *Biosource Technology*, 99, 7928-7940

Vavilin, V.A, Jonsson, S., Ejlertsson, J. and Svensson, B.H. (2006). "Modelling MSW decomposition under landfill conditions considering hydrolytic and methanogenic inhibition." *Biodegradation*, 17 , 389-402.

Yadvika, Santosh, Sreekrishnan, T.R., Kohli,S. and Rana, V. (2004). "Enhancement of biogas production from solid substrates using different techniques—a review." *Bioresource technology* , 95, 1-10

Wang, Y.S., Odlwe, S.I., Eleazer, W.E. and Barlaz, M.A. (1997). "Methane potential of food waste and anaerobic toxicity of leachate produced during food waste decomposition." *Waste Management and Research*, 15, 149–167.

Weiland, P. (2000). "Anaerobic waste digestion in Germany – Status and recent developments." , *Biodegradation*, 11, 415–421

Yılmaz, V. And Demirer, G. N. (2008). “Enhancing the performance of anaerobic digestion of dairy manure through phase-separation." *Clean Technologies.*, 36 (9), 760-766

Zhu, H., Stadnyk, A., Beland, M. and Seto, P. (2008). “Co-production of hydrogen and methane from potato waste using a two-stage anaerobic digestion process”, *Bioresource Technology* , 99, 5078–5084

APPENDIX A

THEORETICAL BIOGAS PRODUCTION CALCULATIONS REGARDING WASTE CONSTITUENTS

Deublein and Steinhauser (2008) suggested that the biogas potential of different constituents are as provided in Table A.1.

Depending on these values, biogas potential of waste can be calculated regarding the measured solid content and the organic content of the waste as follows:

Biogas potential, m^3/ton (D) = Biogas potential of substrate (A)* Solid content of substrate (B) * Organic content of substrate (C) (A.1)

Where, (A); (B) and (C) values are as tabulated in Table A.1:

Table A.1 Biogas potential, solid and organic content of waste streams

Waste Type	Biogas Potential (m^3/ton VS) (A)	Solid content (TS), % (B)	Organic Content (VS/TS), % (C)
WWTP Sludge (liquid form)	500[a]	3.6	79
Green Waste (grass etc.)	575*	18	86
Refused products (crisps)	525*	99	96
Corn Waste	500*	29	96
Potato Waste	500*	20	97
Composite Waste (Substrate)	525[b]	10	90

*Deublein and Steinhauser, 2008; [a] WWTP sludge consists mainly of potato and corn waste; hence biogas potential is assumed to be same as potato and corn waste; [b] Biogas potential of composite waste is calculated as the average of its constituents

Hence, biogas potentials of different waste would be:

- Biogas potential of wwtp sludge, m^3/ton = 500 * 3.6 % * 79 % = 14 m^3/ton
- Biogas potential of green waste, m^3/ton = 575 * 18 % * 86 % = 109 m^3/ton
- Biogas potential of crisps, m^3/ton = 525 * 99 % * 96 % = 148 m^3/ton
- Biogas potential of corn waste, m^3/ton = 500 * 29 % * 96 % = 76 m^3/ton
- Biogas potential of potato waste, m^3/ton = 500 * 20 % * 97 % = 97 m^3/ton
- Biogas potential of starch, m^3/ton = 400 * 92 % * 90 % =331 m^3/ton

Where;

Biogas potential of WWTP sludge is assumed to be same as potato and corn waste, since it consists mainly of potato and corn waste; and biogas potential of composite waste is calculated as the average of the constituents. Constituents of composite waste is assumed as:

- 80 % WWTP sludge
- 12 % Potato waste
- 6 % Crisps
- 2 % Corn waste
- 1 % Green waste

Therefore; biogas potential of composite waste is calculated to be:

Biogas potential $_{composite}$, m^3/ton = ((14 * 80) + (97*12) + (148* 6) + (76*2) + (109*1)) /100

= 34 m^3/ ton of waste

APPENDIX B

COMPARISON OF THEORETICAL VERSUS EXPERIMENTAL BIOGAS PRODUCTION CALCULATIONS

Regarding waste stream

Since the calculations made in Appendix A are based on the assumption of 60 % methane containing biogas; and having actual methane content of ACF biogas as 65 % :

Biogas potential $_{composite}$, m^3/ton = 34 * 65/60
= 37 m^3/ ton of waste

Experimenting with Organic Loading Rates of 3.3; 5.3 and 6.4 kg VS/m^3.d; biogas production rates of 114 L/d; 207 L/d and 246 L/d have been obtained respectively. Related biogas yield values have been found out as 0.396; 0.431 and 0.200 L/g VS added.

Amount of waste fed to the reactors for achieving Organic Loading Rates of 3.3; 5.3 and 6.4 kg VS/m^3.d was; 3 kg/d, 3 kg/d and; 6.3 kg/d respectively.

Theoretical calculations provided the biogas production value 37 m^3/ton of waste = 37 L /kg of waste; for a waste mixture of 80 % WWTP sludge; 12 % Potato waste; 6 % Crisps; 2 % Corn waste; 1 % Green waste.

Daily theoretical biogas production rate, L /d = Waste amount, kg/d * 37 L /kg (B.1)

- For OLR = 3.3 kg VS/m^3.d
  Waste amount = 3 kg
  Waste composition = 90 % WWTP sludge; 6.5 % Potato waste; 3 % Crisps; 0.5 % Corn waste
  Methane content = 70 %

Theoretical biogas production,m^3/ton = ((14 * 80) + (97*6.5) + (148* 3) + (76*0.5) = 22.3 m^3/ton = 22.3 L /kg

Correcting for methane content;

Theoretical biogas production,m^3/ton = 22.3 * 70/60 = 26 L kg

Theoretical biogas production = 26 L /kg * 3 kg/d = 78 L /d

Experimental biogas production = 114 L / d

- For OLR = 5.3 kg VS/m^3.d

  Waste amount = 3 kg

  Waste composition = 82 % WWTP sludge; 5.5 % Potato waste; 0.5 % Crisps; 6 % Corn waste; 6% starch

  Methane content = 67 %

  Theoretical biogas production,m^3/ton = ((14 * 82) + (97*5.5) + (148* 0.5) + (76*6) + (331*6)) /100 = 42 m^3/ton = 42 L /kg

  Correcting for methane content;

  Theoretical biogas production,m^3/ton = 42 * 67/60 = 47 L kg

  Theoretical biogas production = 47 L /kg * 3 kg/d = 141 L /d

  Experimental biogas production = 207 L / d

- For OLR = 6.3 kg VS/m^3.d

  Waste amount = 8.5 kg

  Waste composition = 82 % WWTP sludge; 7 % Potato waste; 2 % Crisps; 7 % Corn waste; 2% starch

  Methane content = 65 %

  Theoretical biogas production,m^3/ton = ((14 * 82) + (97*7) + (148* 2) + (76*7) + (331*2)) /100 = 33 m^3/ton = 33 L /kg

  Correcting for methane content;

  Theoretical biogas production,m^3/ton = 33 * 65/60 = 36 L/ kg

  Theoretical biogas production = 36 L /kg * 8.5 kg/d = 305 L /d

  Experimental biogas production = 246 L / d

Regarding COD removal

Khanal (2008) stated that 1 kg COD destroyed produces 0.35 m^3 of CH_4 at standard temperature and pressure. This means that:

Methane production (m^3) = COD destroyed (kg) * 0.35 m^3/kg (B.2)

Biogas production (m^3/d) = Methane production (m^3) * Methane content of biogas (%) (B.3)

Biogas production (m^3/d) = COD destroyed (kg) * 0.35 m^3/kg * Methane content of biogas (%) (B.4)

Taking temperature and pressure factors into consideration:

Biogas production (m^3/d) = COD destroyed (kg) * 0.35 m^3/kg * Methane content of biogas (%) * ($T_{reactor}$ + 273 /273 K) * (1.01/$P_{reactor}$) (B.5)

where;

COD destroyed (kg/d) = (COD_{in} – COD_{out} (mg/L.d)) / 10^6 (mg/kg) * $V_{reactor}$ (L) (B.6)

Hence;

Biogas production (m^3/d)=(COD_{in} – COD_{out} (mg/L.d)) / 10^6 (mg/kg) * $V_{reactor}$ (L) * 0.35 m^3/kg*Methane content of biogas (%)*(($T_{reactor}$ + 273) /273 K) * (1.01/$P_{reactor}$) (B.7)

Since T = 28 ^{0}C and P = 12 atm for all experiments;
Temperature correction factor = (28+273)/273 = 1.1
Pressure correction factor = 1.01/12 = 0.084

- For OLR = 3.3 kg VS / m^3.d:

Methane content of biogas = 70 %; $V_{reactor}$ = 90 L; COD_{in} = 135900 mg/L;
COD_{out} = 45600 mg/L

COD destroyed (kg/d) = (135000- 45600) / 10^6 * 90
= 8 kg/d

Biogas production (m^3/d) = 8 kg/d * 0.35 m^3/kg * 0.7
= 1.96 m^3/d at 25 ^oC.

Correcting for temperature and pressure;
Biogas production (m^3/d) = 1.96 m^3/d * (301 K / 273 K) * (1.01/12) = 0.182 m^3/d

- For OLR = 5.3 kg VS / m^3.d :
  Methane content of biogas = 67 %; $V_{reactor}$ = 90 L; COD_{in} = 88000 mg/L;
  COD_{out} = 38000 mg/L

  COD destroyed = (88000- 38000) / 10^6 * 90
  = 5 kg/d

  Biogas production (m^3/d) = 5 kg/d * 0.35 m^3/kg * 0.67
  = 1.17 m^3/d at 25 ^oC.

  Correcting for temperature and pressure;
  Biogas production (m^3/d) = 1.17 m^3/d * 1.1 * 0.084 = 0.109 m^3/d

- For OLR = 6.4 kg VS / m^3.d:
  Methane content of biogas = 65 % ; $V_{reactor}$ = 190 L; COD_{in} = 111000 mg/lt
  COD_{out} = 42500 mg/lt

  COD destroyed = (111000- 42500) / 10^6 * 190
  = 13 kg/d

Biogas production (m^3/d) = 13 kg/d * 0.35 m^3/kg * 0.65

= 2.96 m^3/d at 25 ^oC.

Correcting for temperature and pressure;

Biogas production (m^3/d) = 2.96 m^3/d * 1.1 * 0.084 = 0.274 m^3/d

APPENDIX C

ENERGY CALCULATIONS FOR ANAEROBIC CO-DIGESTION FACILITY

Equations used for energy calculations and related energy values are tabulated in Table C.1

Table C.1 Energy Calculations

	Unit	Parameter	Equation	Value
Biogas balance				
ACF biogas production	m^3/yr	A		2,800,000
ACF biogas production	m^3/hr	B	A/(365 d/yr)/(24 hr/d)	320
Microturbine biogas consumption	m^3/hr	C		40
Microturbine biogas consumption	m^3/yr	D	C* (365 d/yr)*(24 hr/d)	350,400
Gas engine biogas consumption	m^3/hr	E		140
Gas engine biogas consumption	m^3/yr	F	E* (365 d/yr)*(24 hr/d)	1,226,400
Boiler biogas consumption	m^3/hr	G		20
Boiler biogas consumption	m^3/yr	H	G* (365 d/yr)*(24 hr/d)	175,200
Energy need				
ACF heat energy need	kwh	I	I	160
ACF heat energy need	kWh/yr	ACF_{heat}	I* (365 d/yr)*(24 hr/d)	1,401,600
ACF electrical energy need	kwh	K		60
ACF electrical energy need	kWh/yr	ACF_{el}	K* (365 d/yr)*(24 hr/d)	525,600
Total energy need	kWh/yr	ACF_{energy}	$ACF_{heat}+ACF_{el}$	1,881,951
Cogeneration energy yield (microturbine)				
Number of microturbines	Unit	M		1
Microturbine electrical output	kW/unit	N		65
Microturbine electricity generation	kWh/h	O	M*N	65
Microturbine electrical efficiency	%	P		30

Table C.1 Energy Calculations (continued)

	Unit	Parameter	Equation	Value
Microturbine heat efficiency	%	Q		50
Microturbine heat generation	kWh/h	S	Q*R	98
Total microturbine electricity generation	kWh/yr	M_{el}	O* (365 d/yr)*(24 hr/d)	569,400
Total microturbine heat generation	kWh/yr	M_{heat}	S* (365 d/yr)*(24 hr/d)	854,100
Cogeneration energy yield (gas engine)				
Gas engine	Unit	T		1
Gas engine electrical output	kW/unit	U		330
Gas engine electricity generation	kWh/h	V	T*U	330
Gas engine electrical efficiency	%	X		40
Gas engine net electricity generation	kWh/h	Y	V*X	132
Gas engine heat efficiency	%	Z		47
Gas engine heat generation	kWh/h	ii	Y*Z	155
Total gas engine electricity generation	kWh/yr	G_{el}	V* (365 d/yr)*(24 hr/d)	2,890,800
Total gas engine heat generation	kWh/yr	G_{heat}	ii* (365 d/yr)*(24 hr/d)	1,358,676
Boiler energy yield				
Boiler biogas consumption	m^3/yr	H		175,200
Natural gas conversion factor		F		1
Natural gas equivalent	m^3/yr		H*f	113,880
Boiler energy generation	kWh/h	iii		150

Table C.1 Energy Calculations (continued)

	Unit	Parameter	Equation	Value
Boiler energy generation	kWh/yr	iv	iii* (365 d/yr)*(24 hr/d)	1,314,000
Boiler heat efficiency	%	v		90
Boiler heat energy generation	kWh/yr	B_{heat}	iv*v	1,182,600
Net energy yield				
Co-generation net electrical energy yield	kWh/yr		$M_{el}+G_{el}-ACF_{el}$	2,934,600
Co-generation net heat energy yield	kWh/yr		$M_{heat}+G_{heat}-ACF_{heat}$	1,827,555
Electrical energy produced	kWh/yr		$M_{el}+G_{el}$	3,460,200
Heat energy produced	kWh/yr		$M_{heat}+G_{heat}$	3,229,155
Green energy produced	kWh/yr		$M_{el}+G_{el}+M_{heat}+G_{heat}$	6,689,355
Green energy used	kWh/yr		$ACF_{el}+ACF_{heat}$	1,927,200
Base case				
Net green energy	kWh/yr		$(M_{el}+G_{el}+M_{heat}+G_{heat})-(ACF_{el}+ACF_{heat})$	4,762,155