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Anaerobic Codigestion of Municipal Wastewater Sludge
and Restaurant Grease

by

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Dedication

To my dear parents: Dr. Huanzhong Liu and Ms. Shumin Lv,

Thanks so much for your great efforts to bring me up and your spiritual and material support to my study abroad! I love you forever.

To my dear Shujie Ren,

It is amazing to meet you in Canada. I am very grateful for your accompanying in the past two years and a half and my difficult period in Canada. Thanks so much for the colourful life you brought to me during that period! No matter what happens to you in the future, you are always my best friend and I am always there for you.

Abstract

Anaerobic codigestion of municipal wastewater sludge and restaurant grease was investigated in a semi-continuous lab-scale digestion experiment under mesophilic conditions (37 °C). Compared to the control digester, chemical oxygen demand (COD) loading rate for test digester was elevated to 387% (organic loading rate 4.235 kgVS/m^3/d) and led to 467% increase in daily biogas production, 25.2% increase in methane yield (based on VS deduction), 29.8% increase in COD reduction rate and 27.2% increase in VS reduction rate, respectively. Methane content ranged from 62% to 67%. There was no negative effect of grease addition on the digester performance in this experiment. The great increases in biogas production and methane yield indicated enhanced digestion performance. In addition, partial alkalinity and pH proved to be good indicators to monitor digestion process and predict overloading.

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

1.1 General Introduction

Instead of the conventional treatment methods, landfilling and incineration, anaerobic digestion has become the first treatment option for dealing with most organic wastes (Lettinga, 2005). This is because it has been proved to be a reliable and mature technology and it is able to stabilize most organic wastes effectively and economically. However, more importantly, it is attributed to its environmental and energy benefits, such as greenhouse gas reduction and energy recovery (Weiland, 2010). In the current context of growing concern about global warming and sustainable development of energy supply, the multiple advantages of anaerobic digestion make it more attractive in waste management and treatment.

It is known to all that the investment for new anaerobic digestion facilities is huge. Therefore, fully utilizing the existing facilities becomes an interesting alternative. In addition, in order to upgrade anaerobic digesters into bioenergy power facilities, enhancement of biogas production in digesters has drawn much attention (Schwarzenbeck et al., 2008). Considering these circumstances, codigestion was proposed and has been developed for three decades. It is commonly implemented in the digesters originally treating municipal wastewater sludge (MWS), organic fraction of municipal solid wastes (OFMSW), and animal manure by adding substrates with a high energy content (Mata-Alvarez et al., 2000). Codigestion is mainly featured by boosted biogas production, increased cost-efficiency, and enhanced digestion of the treated wastes.

Municipal wastewater treatment plants (WWTPs) are one of the most reasonable and feasible places to implement codigestion, since anaerobic digesters and biogas recovery systems already exist in WWTPs. In fact, in the energy balance sheet of a municipal wastewater treatment plant, power generation through biogas produced during anaerobic digestion of municipal wastewater sludge can roughly cover about 40% of total electricity consumption in the WWTP (Schwarzenbeck et al., 2008). Codigestion is likely to lead to energy independency of the WWTP or even produce surplus energy. Therefore, economic benefits could be realized. Additionally, anaerobic digesters become regional renewable energy facilities, since they recycle energy from organic wastes (Zitomer et al., 2005).

In recent years, restaurant grease (RG) discharged from restaurants, commercial kitchens and food service providers has become a major stream of municipal organic wastes and is widely available in urban areas. In the past, it was mostly deposited at a landfill, however, this has been banned by environmental legislation (Martin-Gonzalez et al., 2010). Incineration is not suitable for disposing of RG due to relative high cost and environmental consideration (Davidsson et al., 2008). Composting had been applied to grease trap wastes, but the wastes need dewatering first (Coker, 2006). Overall, anaerobic digestion is a better option. Especially greasy wastes have been proven to have high methane production potential (Davidsson et al., 2007). Nevertheless, individual digestion of restaurant grease was not viable because of the well-known long-chain fatty acids (LCFA) inhibition to methanogenesis (Davidsson et al., 2008; Loustarinen et al., 2009). Hence, codigestion is the most attractive way of treating restaurant grease. One possibility is codigestion of MWS with restaurant grease at a WWTP due to the availability of restaurant grease in urban areas.

1.2 Objective

In this study, anaerobic codigestion of MWS and restaurant grease was conducted in 20L digesters at about 37 °C. The main objectives are:

1) to identify the potential maximum organic loading rate for codigestion of MSW and restaurant grease;

2) to propose suitable indicators for monitoring codigestion performance and predicting overloading;

3) to evaluate codigestion performance under different organic loading rates derived from the addition of different amounts of restaurant grease;

4) to collect organic loading rate data and codigestion performance data to improve the operation of restaurant grease addition in future pilot-scale test.

2.0 Literature Review

2.1 Anaerobic digestion

Anaerobic digestion (AD) is a process that employs a consortium of facultative and obligate anaerobic microorganisms to oxidise biodegradable organic materials in the absence of molecular oxygen and produce biogas, mainly methane and carbon dioxide. As one of the most cost-effective waste and wastewater treatment technologies, AD has been used to treat a wide range of wastes, including municipal solid waste (MSW) and municipal sewage sludge, agriculture wastes and manures, and organic industrial wastes.

In general, AD posses the following advantages (Metcalf & Eddy, 2003):

1) AD recovers energy from organic wastes in the form of methane, the major component of biogas, which can be utilised as a renewable energy source to generate electricity and heat, be upgraded into vehicle fuel, or be injected into the local natural gas grid (Weiland, 2010). The multiple uses of produced methane can generate revenues and save other fuels.

2) AD has lower biomass yields than aerobic processes and thus requires fewer nutrients. In essence, the wastes volume can be reduced after stabilization through digestion.

3) AD requires less energy than aerobic processes due to no need for oxygen. Furthermore, all energy required for AD operation usually can be provided by produced biogas.

4) AD can be applied to higher loading rates and treat higher-strength organic wastes than aerobic processes. AD can handle both dry and wet wastes.

5) AD mitigates greenhouse gases (GHG) (e.g. methane and carbon dioxide) emission. Methane is a GHG that has a global warming potential 21 times greater than that of carbon dioxide (CO_2) (Tester et al., 2005). Methane produced in AD is captured and burned, and then the overall effect on global warming is reduced. Additionally, using biogas rather than fossil fuels to generate energy reduces net CO_2 emissions, because burning biogas, whose carbon is derived from atmospheric CO_2, does not increase atmospheric CO_2, but merely recycles it (Cannell, 2003). The GHG emission reductions via AD now can be traded on various climate exchanges to obtain carbon credits.

6) Digestate, digested residues from AD of most wastes, can be used as a valuable fertilizer and soil conditioner.

2.1.1 History and development

As reported by 13th-centurry adventurer Marco Polo, Chinese people used covered sewage tanks, an original form of anaerobic digesters, about 2000 years ago (He, 2010). The modern application of AD for waste treatment made its debut about 100 years ago (Wheatley, 1990). However, the last four decades witnessed an increase in the use of AD. Due to soaring oil prices in the 1970s, all forms of renewable energy drew the governments' attention. During this period, numerous academic studies regarding AD were conducted and funded by European and North American governments (Nichols, 2004; Mattocks and Wilson, 2005). Unfortunately, many digesters, constructed for energy production in the United States, failed because of the lack of technical support. In 1980s, energy prices declined and remained low, so governments offered little financial support to renewable energy. Therefore, very few digesters were built in North America, but pilot and demonstration digesters were sequentially studied in Europe (Nichols, 2004; Mattocks and Wilson, 2005). Based on the research and experience in the 1970s and 1980s, the real commercialization of AD started in the 1990s and has continued to the present. The main drivers for AD development are reducing landfill capacities especially in Europe, and promotion of renewable and sustainable energy again by governments due to the environmental concerns and problems caused by fossil fuels utilization (Nichols, 2004). In industrial terms, anaerobic digestion technology is considered to have become mature and reliable (Ruggle, 1998). As of 2005, over 3500 digesters were operated in Germany and about 1000 digesters were under construction (House et al., 2007), which made it the largest biogas producing country in the world (Weiland, 2010).

The research and development of AD largely involves investigation of process microbiology, feasible feedstocks and pretreatment, process technology, biogas utilization, and digestate utilization. Among these, process technology is a hot topic. So far, a large amount of improvements have been achieved in process technology and can be summarized in the following primary features.

1) Number of stages

Single-stage and two-stage digesters are the dominant forms for AD in the current market. For single-stage digestion, all digestion reactions occur in one digester. For two-stage digestion, liquefaction of organic solids, digestion of soluble organic matter and gasification occur in the first stage, while supernatant separation, gas and digested sludge storage are the main functions for the second stage. To offer optimal environments for hydrolysis and methanogenesis, a separate hydrolysis reactor may be added in the beginning of two-stage digestion. Two-stage AD can accommodate higher loading rate and shorter hydraulic retention time at the expense of higher capital and operation cost and more difficult process control (Nichols, 2004).

2) Wet digestion and dry digestion

This classification is based on the total solids (TS) content of the feedstocks. When TS of feedstock is below 15%, it is called wet digestion. Feedstocks for wet digestion are pumpable slurries with higher homogeneity. Dry digestion treats the feedstocks of which TS are in the range of 15% to 35% (Nichols, 2004; Weiland, 2010). Dry digestion contributed to about 54% of the total AD capacity in Europe in 2000 (De Baere, 2000).

3) Operating temperature

The digesters were initially operated in mesophilic temperature range. The first thermophilic digester made its debut in 1992 (De Baere, 2000). Recently, some research has demonstrated the feasibility for AD in psychrophilic temperature range. Detailed discussion is described in Section 2.1.3.

4) Digester type

There are two types of digesters: vertical and horizontal digesters. Vertical continuously stirred tank digester is employed in nearly 90% of modern biogas plants in Germany and is the most widely applied digester type for wet digestion**.** Horizontal digesters are operated in the mode of plug flow and equipped with a low speed rotating horizontal paddle mixer. They can handle higher total solids content of the feedstocks and thus are usually employed as the first stage of a two-stage AD (Weiland, 2010).

5) Codigestion

Codigestion is a modification of AD in which multiple feedstocks are digested together to achieve positive synergism. Co-digestion will be addressed in detail in Section 2.2.

In addition, to improve the performance of digesters treating different feedstocks, numerous pretreatment methods have been applied, including mechanical, biological, thermal, and chemical treatments (Mata-Alvarez et al., 2000; Weiland, 2010).

In both ecological and economical terms, AD has a promising future in the context of an overall sustainable waste management perspective.

2.1.2 Mechanism

As a biological process, the mechanism of AD is described by the complex and various biological conversion activities carried out by the specific consortia of microorganisms. The major domains of the microorganisms involved in AD are facultative and strict anaerobic bacteria as well as methanogens (Bitton, 2005). These microbial groups work in a synergistic relationship and degrade complex organic compounds into simple molecules such as methane and carbon dioxide. The overall reaction for AD is:

$$\text{Organic matter} + \text{Combined oxygen} \xrightarrow{\text{Anaerobic microbes}} \text{New cells} + \text{Energy for cells} + \text{Methane} + \text{Carbon dioxide} + \text{Other end products}$$

Combined oxygen is derived from CO_3^{2-}, SO_4^{2-}, NO_3^{-}, and PO_4^{3-}. Other end products refer to hydrogen sulphide, hydrogen, and nitrogen.

Since these microorganisms can be mainly categorised into four groups, i.e. hydrolytic bacteria, acidogenic bacteria, acetogenic bacteria and methanogens, the AD processes are correspondingly divided into four stages, i.e. hydrolysis, fermentation/acidogenesis, acetogenesis and methanogenesis (Bitton, 2005; Mitchell and Gu, 2010). Figure 2-1 depicts a general scheme of the simplified AD processes.

1) Hydrolysis

In the first stage, hydrolytic bacteria break down complex organic compounds, such as polysaccharides, proteins and lipids, into soluble monomers (e.g. glucose, long-chain carboxylic acids, and amino acids) through enzymatic hydrolysis. The hydrolases involved include cellulase, protease, lipase, and so on. Polysaccharides are generally broken down into simple monomeric or dimeric sugars. Lipids are converted into long-chain fatty acids and glycerol moieties by lipases and phospholipases. Hydrolysis is a relatively slow process and may be a limiting step in digestion processes.

2) Fermentation/acidogenesis

In the fermentation stage, the hydrolysis products are further transformed into short-chain carboxylic acids (mainly acetic, propionic, and butyric acids), alcohols, ketones, carbon dioxide and hydrogen by fermentative (i.e. acid-forming) bacteria. Carbohydrate fermentation generally yields acetate as the main product.

Figure 2- 1 Anaerobic process schematic of hydrolysis, acidogenesis, acetogenesis and methanogenesis (Adapted from Bitton, 2005)

3) Acetogenesis

Acetogenic bacteria (acetate and H_2-producing bacterial or obligate hydrogen-producing acetogens, OHPAs) convert fatty acids and alcohols into acetate, hydrogen, and carbon dioxide in this stage. Importantly, the conversion only performs effectively under low H_2 partial pressure. Otherwise, if the hydrogen concentration is relatively high in the system, the reactions will be reversed by fatty acid-synthesizing bacteria, thus resulting in reduced acetate formation and increased fatty acids formation (Smith and McCarty, 1988).

4) Methanogenesis

Methanogenesis is the final stage in AD processes, where methane is produced by methanogens, strictly anaerobic archaea. Methanogens are subdivided into two categories: (a) acetotrophic or acetoclasic methanogens, including two domain genera: *Methanosarcina* and *Methanosaeta*, which split acetate into carbon dioxide and methane accounting for approximately 70% of total methane produced during AD (Lettinga, 1995). (b) hydrogenotrophic methanogens (i.e. hydrogen-using chemolithotrophs), which reduce carbon dioxide by hydrogen into methane accounting for about 30% of total methane production. Additionally, there are a limited number of other substrates utilized by methanogens, such as methanol, methylamines and formate.

There is a symbiotic relationship between methanogens and OHPAs. Methanogens can consume most hydrogen in the system and maintain the low hydrogen concentration required by OHPAs. Also, OHPAs can convert fermentation intermediates (mainly fatty acids) to methanogenic substrates. If the methanogens do not consume the produced hydrogen fast enough, the propionate and butyrate fermentation will be slowed down and result in the accumulation of volatile fatty acids, a pH drop and possible process upsets.

The biogas produced in AD comprises about 55%-75% methane, about 25%-45% carbon dioxide, and trace amounts of hydrogen sulphide, hydrogen, and nitrogen (Reynolds and Richards, 1995).

2.1.3 Operation conditions, inhibition and monitoring

Operational stability is crucial for successful AD. As discussed in Section 2.1.2, four groups of microorganisms are involved in AD. Maintaining suitable living conditions for these microorganisms and the balance among them are essential to achieve operation stability.

pH and temperature are the most significant factors to evaluate living conditions for microorganisms. Neutral pH value, ranging from 6.7 to 7.4, is preferred for methanogens and below 6.8 the methanogenic activity is inhibited (Metcalf & Eddy, 2003). If pH decreases to 6.0, AD process may fail. For full-scale anaerobic digesters, pH is maintained above 6.8 (Bjornsson et al., 2000).

Temperature is important due to its influence to the rate of digestion, particularly the rates of hydrolysis and methane formation. The majority of AD systems are applied in mesophilic temperature range of 30-38 °C, or thermophilic temperature range of 50-57 °C (Metcalf & Eddy, 2003). In these two temperature ranges, microorganisms involved in AD can function optimally. Mesophilic process is the most commonly used in AD systems, because microorganisms in this temperature range can endure more operation fluctuations and operation stability is relatively easier to achieve compared to thermophilic process. However, despite higher energy cost, thermophilic process is still attractive because of higher microorganism activity, higher loading rate and greater destruction of pathogens (Bitton, 2005). Additionally, in recent years, low-temperature AD process (0-20 °C) has emerged and been reported to achieve satisfactory digester performance in treatment of animal manures, slurries and wastewater (Collins et al., 2006; Masse et al., 2007).

The so-called inhibitors are the substances that can adversely change the living conditions which are suitable for microorganisms or inhibit microorganisms' growth or upset the balance among different groups of microorganisms. Inhibition in AD is usually identified by decreased methane content and production and increased concentration of volatile acids. There is a long list of inhibitors to AD, such as ammonia, sulphide, light and heavy metals, and various organic compounds **(**Chen et al., 2008). The most common inhibitors encountered are ammonia and sulphide.

Ammonia is of concern when treating the wastes that contain high concentrations of proteins, urea or ammonium. Between the two major forms of ammonia in aqueous solution, free ammonia is more toxic than ammonium ion, especially for methanogens (Metcalf & Eddy, 2003). High concentrations of ammonia in AD system may change the intracellular pH, increase maintenance energy requirement and reduce a specific enzyme's activity, thus resulting in ammonia inhibition (Whittmann et al., 1995). Therefore, ammonia concentration is measured as an indicator to monitor AD process.

Sulphide in AD is mostly derived from the sulphate reduced by the sulphate reducing bacteria (SRB). Since sulphate exists in a wide range of wastewater and organic wastes that are treated with AD, sulphide is often found in digestion biogas and effluent. When sulphide concentration exceeds 200 mg/L, it is toxic to methanogens (Bitton, 2005). Another more important inhibition related with sulphide is due to competition between SRB and methanogens. They share the same substrates, i.e. acetate and hydrogen. However, when acetate concentration is low, methanogens are less competitive than SRB and their growth will be slowed down. Methanogens and SRB can maintain a balance at COD/SO_4 ratios of 1.7-2.7 (Bitton, 2005). Hydrogen sulphide is usually monitored in biogas or in digestion effluent to evaluate the sulphide level in AD system.

Monitoring plays a key role in inspecting the stability of AD process and identifying AD upsets, such as overloading and inhibition. Because of the complexity of the AD process, it is difficult to find a simple and suitable indicator to evaluate the whole process. Commonly several indicators are monitored together and provide complementary information. The widely accepted indicators include pH, alkalinity, volatile fatty acids (VFA), biogas production, COD, VS, and the concentrations of methane and carbon dioxide in biogas. Among them, VFA is considered as an efficient indicator for overloading and process imbalances (Bjornsson et al., 2000), but VFA measurement is a slow procedure and online measurement is not practical right now (Weiland, 2010). As discussed above, pH is another important indicator. It can reflect system changes relatively quickly and the measurement of pH is easy and fast. Alkalinity is largely produced in the stage of methanogenesis and from the breakdown of organic nitrogen (mainly protein) (Metcalf & Eddy, 2003). Alkalinity indicates the buffering capacity of AD system. Especially, partial alkalinity (PA) is more sensitive than total alkalinity (Bjornsson et al., 2000). COD and VS are primary parameters to measure organic loading. Sometimes, to identify the causes of inhibition, some specific substances are measured, such as hydrogen sulphide and metals.

2.2 Anaerobic codigestion

2.2.1 Introduction

Codigestion, as a modification of anaerobic digestion, is used to handle several solid or liquid organic wastes together in a single digester. The treated waste mixtures comprise one main waste and one or more codigestates. The main waste, generally low-strength, is added in large quantity and may contribute the major organic loading, while codigestates are usually high-strength wastes and added in smaller amounts. The most common main wastes used in codigestion are municipal wastewater sludge (MWS) (i.e. sewage sludge), organic fraction of municipal solid wastes (OFMSW), and animal manure (Mata-Alvarez et al., 2000). Since the three wastes were initially treated singly using anaerobic digestion in the past, there are many existing digesters, where codigestion is much easier to perform (Alatriste-Mondragon et al., 2006). Codigestates are more diverse and include numerous organic solid wastes, such as food wastes, cattle manure and poultry wastes, slaughterhouse wastes, agricultural wastes, paper mill wastes and wood wastes (Alatriste-Mondragon et al., 2006). The added codigestates can provide additional nutrients and stimulate digestion processes, thus enhancing digestion efficiency and biogas yield.

Since the late 1980s, animal manure has been codigested with industrial organic wastes in Denmark (Danish Energy Agency, 1995). In the 1990s, codigestion studies were extended to MWS, OFMSW, olive oil mill wastewaters and other organic wastes, such as agricultural wastes, kitchen wastes, slaughterhouses and meat processing wastes (Demirekler and Anderson, 1998; Di Palma et al., 1999; Poggi-Varaldo et al., 1997; Sundararajan et al., 1997; Angelidaki and Ahring, 1997; Brinkman, 1999). However, codigestion capacity occupied less than 7% of total anaerobic digestion capacity in Europe up to 1999 (De Baere, 2000).

In recent years, the range of codigestates keeps expanding. In food industry, beet-pulp, rumen fluid, desugared molasses, cheese whey, fruit and vegetable wastes are utilised (Alkaya and Demirer, 2011; Alrawi et al., 2010; Fang et al., 2010; Kavacik and Topaloglu, 2010; Rizk et al., 2007). Newly studied agricultural wastes include turf cutting litter, corn stalk, corn stover, wheat straw, grass silage, sugar beet tops and oat straw, (Xie et al., 2010; Chen et al., 2010; Li et al., 2009; Wang et al., 2009; Lehtomaki et al., 2007). Industrial wastes are extended to glycerol, pharmaceutical waste fermentation broth and leather fleshing (Fountoulakis et al., 2010; Zupancic and Gotvajn, 2009; Shanmugam and Horan, 2009).

In terms of methane yield potential, some research found that codigestates rich in lipids and easily-degradable carbohydrates have the highest potential, while more recalcitrant codigestates with a high lignocellulosic fraction have the lowest potential (Labatut et al., 2010). Hence, fat, oil and grease (FOG) from food industrial wastes or OFMSW, is an extremely attractive codigestate and has been studied both in lab-scale experiments but also applied to full-scale digesters recently (Kabouris et al., 2008; Lansing et al., 2010; Bailey, 2006).

Generally, codigesion provides a new manner to simplify and integrate waste management, while efficiently recovering energy and nutrients via biogas and digestates. However, before codigestation is implemented, careful considerations should been taken. Codigestion may adversely affect the quality of the digestates by introducing undesirable components and may offer possible new routes for disease spread, thus leading to disposal problems for digestates (Nowak, 2006; Luostarinen et al., 2008).

2.2.2 Benefits

2.2.2.1 General benefits

Anaerobic codigestion offers more benefits than conventional anaerobic digestion.

The most attractive benefit of anaerobic codigestion is that it can increase the biogas yield due to a positive synergistic effect between the main waste and codigestates. In most cases codigestion increases methane yield, and in a few cases hydrogen yield (Sang-Hyoun et al., 2004; Heguang et al., 2008; Zitomer et al., 2008). The synergistic effect may result from supplement of necessary nutrients, alkalinity and moisture contents (Zitomer et al., 2008), attenuation of inhibition (Callaghan et al., 1999), or high concentration of microorganisms and high level of microbial activity in codigestion system. There are a number of extra benefits related to the increase of biogas yield. The more biogas produced, the more energy is generated and recovered, the more GHG emission reductions are achieved, the more carbon credits are obtained, and finally more revenue is generated.

Another benefit also stemming from the synergistic effect lies in the fact that codigestion can stabilize and enhance the digestion process, resulting in the reduction of the residual solids production (Davidsson et al., 2008).

In addition, codigestion provides a cost-effective and energy-yielding way to handle certain codigestates, which are poorly biodegradable and hard to digest individually.

Last but not least, codigestion, if performed using existing equipment, will save capital and management cost, because of reduced need for new investment.

2.2.2.2 Benefits for WWTPs

A large number of anaerobic digesters are employed at WWTPs all over the world today to treat MWS, which is produced in large quantity and is reasonably considered as the main waste of codigestion. Generally, most of digesters in WWTPs are oversized and it is viable to fully utilize their spare capacity through codigestion (Nowak, 2006; Bolzonella et al., 2006). Furthermore, biogas is already being produced by anaerobic digesters in WWTPs and utilized to recover energy, so biogas recovery systems are also available in WWTPs. Therefore, the existing anaerobic digesters and relative biogas recovery equipment can be directly used for codigestion, leading to more efficient use of equipment, cost-sharing by treating wastes from multiple origins in a single facility, thereby enhancing the economics of biogas production (Zitomer et al., 2008). In terms of operation and equipment, codigestion can be easily implemented in WWTPs with little upgrade cost.

In addition, when used for codigestion, anaerobic digesters become regional renewable energy facilities (Zitomer et al., 2005), since they recycle energy from organic wastes.

In economic terms, codigestion not only provides considerable saving in the overall energy costs for plant operations, but also adds extra revenue for WWTPs. This will be discussed in Section 2.5.

2.3 Restaurant Grease

Restaurant grease (RG) is fats, oils and grease (FOG) discharged from restaurants, commercial kitchens and food service providers. It is commonly classified as yellow grease and brown grease. Yellow grease refers to wasted cooking oil. Brown grease refers to grease trap and interceptor wastes, which consist of yellow grease, food solids, and water (Fonda et al., 2004).

According to the study by the National Renewable Energy Laboratory in 1998, the quantity of RG would approach 1 billion kilograms annually based on about 200 million sewered population in the United States (Wiltsee, 1999). In the past ten years, the number of restaurants keeps increasing with continuously increasing population. Thus, RG has become a major stream of municipal organic wastes and is widely available in urban areas. Meanwhile, the fate of RG has become one of the most critical concerns in waste management, since RG has caused severe problems in municipal wastewater collection and treatment systems, and is extremely hard to dispose of (Stoll and Gupta, 1997; Fonda et al., 2004; Parnell, 2006).

2.3.1 Problems caused by restaurant grease

Generally, greasy wastes are not environmentally friendly. They cause an odour nuisance and have adverse or to some extent toxic effect on marine life and birds. Moreover, they are slow to degrade naturally. Thus, efforts should be made to keep them out of the environment.

More importantly, RG has caused serious problems in waste management and municipal wastewater collection and treatment systems. Because of the sticky nature of RG, it forms undesirable deposits in drain pipes and sewer lines, and tends to block and gradually corrode them. It was reported that 75% of the sewer systems in the United States worked at only half capacity due to grease clogs, which decreased the flow through the lines and might lead to sewer overflows (Russell, 2002; Hamkins, 2006). Furthermore, if RG reaches the municipal wastewater treatment plants in large quantity, it would float on the surface of wastewater and stick to pipes and walls, consequently clogging strainers and filters, and interfering with the unit operations (Stoll and Gupta, 1997). Additionally, high grease concentration in wastewater causes foaming problems (Rutt et al., 2005). Even treated in anaerobic digesters, RG has the potential of accumulating into a thick layer at the top of the digester, if the provided turbulence is not strong enough. This requires periodic cleaning for digesters (Joyce and Donaldson, 2005).

Additionally, RG, usually composed of long chain fatty acids, is a group of more stable organic compounds which are difficult to break down biologically and for waste treatment plants to handle.

2.3.2 Management and disposal

As stated above, RG can be a major maintenance issue, leading to sewer overflows and deteriorating performance of wastewater treatment systems. Municipalities have taken some actions to monitor RG production and storage, reduce the amount of RG entering municipal wastewater collection and treatment systems and seek manageable and beneficial ways to collect and treat RG. For example, in some states of the United States, installation of grease interceptors instead of traditional grease traps is mandatory for new restaurants; interceptors and grease traps should be installed with monitors and cleaned at a minimum of every 90 days; grease haulers should be regulated and tracked (Russell, 2002; Parnell, 2006). Another change is in the way of transportation. Grease could be collected and picked up from restaurants by special trucks or haulers and directly delivered to treatment plants (Fonda et al., 2004).

In the long managerial chain for RG, how to dispose of RG is the most significant node. An effective regulation regarding RG or a viable RG reduction program depends on whether the final methods of RG disposal are cost-effective or not. Various options exist for handling RG.

For yellow grease, rendering companies can process it to produce tallow, supplement fat in animal feed and low grade machine lubricants. It can also be reused in the soap industry as an additive (Wiltsee, 1998). Nowadays, some environmentally beneficial and cost-effective methods have been put forward. Among them, the popular ones are using grease as a supplemental fuel, using grease to produce biodiesel, and digesting grease to produce biogas (Hamkins, 2006).

Brown grease is produced in larger quantity and has more complex components, containing not only FOG but also water and solids. Theoretically, as long as FOG part in brown grease can be effectively concentrated and separated, the reuse and disposal methods for yellow grease can be applied to the FOG part. It has been demonstrated that fractionation tanks and dewatering containers could concentrate brown grease in pilot tests (Hamkins, 2006). However, the residual material still needs to be properly disposed.

When used as supplemental fuels, FOG must be concentrated to remove water content and increase its heat content. Biodiesel is typically made from yellow grease or food-grade vegetable oils, which are not cheap for real application. Brown grease has the potential of producing biodiesel once it goes through proper pretreatments, but the technology is not mature enough (Hamkins, 2006; Canakci, 2007).

Biogas generation, usually performed in anaerobic digesters in wastewater treatment plants and biogas plants, is more economically and technologically feasible today. Generally, without pretreament, any kind of grease streams can be directly fed into the digesters (Hamkins, 2006). However, it is hard to digest FOG separately, so commonly FOG is added into existing digesters as a supplemental feedstock. This will be discussed in the following section.

2.4 Development of anaerobic codigestion of municipal wastewater sludge and FOG

For the past two decades, FOG has not been a stranger to WWTPs. Most FOG flows into WWTPs together with sewage. It is usually removed in primary sedimentation tanks with other floatable materials. The collected scum is commonly pumped into anaerobic digesters as part of feedstocks (Fonda et al., 2004). Nevertheless, this does not frequently happen and has little effect on the anaerboic digestion performance and biogas production. Since the late 1990s, some researchers have explored the realm of anaerobic codigestion of municipal wastewater sludge and FOG in studies ranging from lab-scale tests to full-scale applications. FOG addition has become routine in some WWTPs and largely influenced energy and economic balance of these WWTPs.

Machuzak (1997) digested primary MWS with FOG (2.7% volatile suspended solids loading) and reported an increase of the biogas production of up to 21%. These results seemed to indicate that codigesting FOG with MWS improved their overall biodegradability.

Suto et al. (2006) performed laboratory digestion of FOG and combined municipal primary sludge and thickened waste activated sludge. The results showed a stable digestion at a volumetric loading of 35%, based on the total FOG plus sludge feed volume. Under mesophilic conditions (35 °C), biogas increase was 94%, which was higher than 80% increase under thermophilic conditions (50 °C).

Kabouris et al. (2008) conducted lab-scale experiments under batch and semicontinuous feeding conditions to assess the anaerobic biodegradability of municipal primary sludge (PS), thickened waste activated sludge (TWAS) and FOG obtained from restaurant grease traps, and the corresponding methane yield (Kabouris et al., 2008; Kabouris et al., 2009a; Kabouris et al., 2009b). They found that the addition of FOG (48% total volatile solid loading) to a PS + TWAS mixture yielded 449 mL methane (at standard temperature and pressure, STP) /g volatile solid (VS) added at 35 °C and 512 mL methane (at STP) /g VS added at 52 °C, that is, 2.9 and 2.6 times increase, respectively. The results demonstrated the feasibility of beneficial use of FOG through codigestion with MWS, the enhancement of sludge digestion during codigestion, and the crucial effect of FOG loading on methane yield.

Anaerobic codigestion of grease traps sludge and MWS from the largest WWTP in Malmö, Sweden, was successfully performed both in laboratory batch tests and in continuous pilot-scale digestion tests (Davidsson et al., 2008). Single-substrate digestion of grease trap sludge gave high methane potentials in batch tests (845-928 mL/gVS), but could not reach stable methane production in the continuous digestion tests. However, when 10-30% (VS) of grease traps sludge was codigested, the methane yield increased 9-27% without increasing the residual sludge production.

Luostarinen et al. (2008) assessed the feasibility of codigesting grease traps sludge from a meat-processing plant and sewage sludge under batch and semi-continuous feeding conditions at 35 °C. The viable added grease trap sludge proportion could go up to 46% of total feed volatile solids (organic loading rate 3.46 kgVS/m^3•d). However, when it reached 55% and 71%, degradation was not complete and methane production either remained the same or decreased.

The codigestion of MSW and FOG has been implemented in several full-scale WWTP anaerobic digesters for improving biogas production. Most published reports indicated this application was very popular in California. For instance, the Millbrae Water Pollution Control Facility, in Millbrae, California, was designed to receive about 11m^3 (3000 gal) of grease a day.

Based on over 4 years of grease-digestion experience, Cockrell (2008) reported a more than 50% increase in biogas production at a full-scale digestion facility in the City of Watsonville, California, after accepting and codigesting sludge and FOG at an FOG loading rate of 0.48 kg-VS/m^3•d.

The City of Riverside, California, began the Grease to Gas to Power project in April 2005, by adding grease wastewater collected from restaurants to the anaerobic digestion process (Bailey, 2006). The methane gas concentration was elevated from 53% to 67% and the average heat value of the methane increased from 565 to 660 kJ. The diurnal volume of methane gas produced in the grease digester increased by 133% with a peak of 13960 m^3 (493,000 ft^3). In addition, overall biosolids production in treatment process was reduced by about 25 percent, since the population of methanogens has boomed dramatically after introduction of grease wastewater into digesters.

2. 5 Economic analysis

The economic analysis here is on behalf of WWTPs that implement codigestion with FOG. Generally, when RG is treated in anaerobic digesters at WWTPs, the revenue or saving streams are from dump fees or tipping fees for receiving grease, increased power generation due to enhanced biogases production and reduced fossil fuel purchases. On the other hand, capital cost as well as operation and maintenance cost to implement codigestion should be taken into account.

The South Bayside System Authority (Redwood City, California) uses an anaerobic digester system to treat 3800 m^3 (1 million gal) of greasy waste annually, generating revenue of nearly \$200,000 per year (Joyce and Donaldson, 2005), almost half of which is from power generation. The utility has reportedly generated about 0.15 m^3 of digester gas per litre of grease (20 ft^3 of digester gas per gallon of grease). This digester gas was used as fuel in cogeneration facilities to generate power valued at about \$0.09 per digested gallon grease.

The renovation undergone in Millbrae Water Pollution Control Facility was expected to produce as much as 80 percent of the electricity used by Millbrae's WWTP, about 1.5 million kWh per year (Landers, 2005). Annually, the revenue would generate approximately \$264,000 from energy savings and fees paid by grease haulers, while the project cost \$ 5.5 million to design and construct the grease receiving station, micro-turbine cogeneration system, and other related facilities. According to conservative calculations using 2004 energy prices, it would take 20 years to recover the initial investment in the form of energy savings.

Since early 2003, grease has been fed to the digesters in the City of Watsonville, California. The project revenue is derived from the grease tipping fees and avoided natural gas purchases. From 2003 to 2006, grease revenue totalled $250,000 and natural gas saving reached about $450,000 (Cockrell, 2008). The actual capital cost was $271,000, thus payback period was less than 2 years.

The Grease to Gas to Power project in City of Riverside, California, received about 113 m^3 (30,000 gallons) per day of grease wastewater from restaurants throughout southern California. The electrical power generation of about 1.6 megawatts per day is enough to provide the electrical needs of 1,203 homes for one month. This project has reduced the natural gas requirements of the cogeneration power system by 80 percent. This yielded a monthly savings ranging from $80,000 to $85,000. Annually, the energy cost reduction created by this project was almost $1,000,000 (Bailey, 2006).

3.0 Materials and Methods

3.1 Materials

The materials used in all experiments are tabulated in Table 3-1.

Table 3- 1 Materials for experiments

Materials	Product identification and suppliers
Mercuric sulfate	M1901-100, Fisher Scientific
Potassium dichromate	P188-500, Fisher Scientific
Silver sulfate	S190-100, Fisher Scientific
Sulphate acid	ACS-Pur, Fisher Scientific
Potassium hydrogen phthalate	100g, Fisher Scientific
Sodium carbonate	S263-500, Fisher Scientific
Sodium acetate	241245-100g, Sigma
Sodium propionate	P1880-500g, Sigma
Iso-butyric acid	100 ml, Sigma
N-Butyric acid	100 ml, Sigma
N-valeric acid	100 ml, Sigma
Iso-valeric acid	100 ml, Sigma
Sodium hydroxide solution	12064-500, Fluka Analytical
Nitrogen	4.8, Praxair
Helium	4.5, Praxair
Carbon dioxide	3.0, Praxair
Methane	2.0, Praxair

Several different wastes were also used in the experiments.

1) Seed sludge

To start up the lab-scale digesters, digested sludge was used as seed sludge. It was the effluent of a full-scale anaerobic digester at Goldbar Wastewater Treatment Plant (WWTP) in Edmonton, AB. Seed sludge was taken from Goldbar and directly transported to the lab in University of Alberta to start the experiments.

2) Feed sludge

Feed sludge was also obtained from Goldbar WWTP and comprised 75% (v/v) primary treatment sludge and scum and 25% (v/v) thickened waste activated sludge. The mixture was blended well before feeding the digesters. Feed sludge was delivered to the lab once a month and kept in a cold room at 4 °C to minimize the bacterial activity.

3) Restaurant grease

Restaurant grease (RG) was a collection of a few restaurant grease traps in Edmonton, provided by Suck-U Sump Service Ltd. A pail of restaurant grease was received and used throughout the whole experiment. It was also kept in the cold room at 4 °C.

3.2 Equipment

Table 3-2 shows the equipment involved in all experiments.

Table 3- 2 Equipments for experiments

Equipments	Types and manufacturers
Spectrophotometer	Novaspec II, Pharmacia Biotech.
COD reactor	Bioscience Inc.
Glass fibre prefilters	AP1504700, Millipore
Nylon membrane	0.45μm, Millipore
Syringe driven filter unit	0.22μm, Millipore
pH meter	AR15, Fisher Scientific
Digital mass flow meter	DFM-500, Challenge Technology
Carboy	20L, Nelgene
Immersion heater	C1, Hakke
Magnetic Mixer	Thernix Stirrer 120S, Fisher Scientific
Barometer	Fisher Scientific
Fyrite CO2 analyzer	Bacharach
Quality sample bag	1L, SKC
Gas Chromatograph	GC-8A, Shimadzu
Ion Chromatograph	Dionex
Refrigerated superspeed centrifuge	Sorvall RC-5B, Du Pont Instruments
Centrifuge tube	PP F-CAP 50ml, Corning Incorporated
Oven	Isotem P 500 Series, Fisher Scientific
Muffle furnace	30400, Thermolyne
Balance	AB204-S/FACT, Mettler Toledo

3.3 Analytical methods

In the experiments, the following 11 parameters were measured: biogas production, pH, partial alkalinity (PA), total alkalinity (TA), total chemical oxygen demand (COD), soluble COD, total solids (TS), volatile solids (VS), methane, carbon dioxide and volatile acids. Analyses were conducted according to the methods listed in Table 3-3.

Table 3- 3 Analytical methods

Analysis	Method
Biogas production	Mass flow meter
pH	pH meter
Partial alkalinity (to pH 5.75)	2320 B[a]
Total alkalinity (to pH 4.3)	2320 B[a]
Chemical oxygen demand (COD)	5220 D[a]
Total solids (TS)	2540G[a]
Volatile solids (VS)	2540G[a]
Methane	Gas chromatography[b]
Carbon dioxide	Fyrite % CO_2 analyzer[c] and Gas chromatography[b]
Volatile acids	Ion Chromatography[d]

a Standard methods for the examination of water & wastewater, 21st Edition, 2005
b See Appendix A.1
c Instruction 11-9026, Bacharach Inc.
d See Appendix A.2

3.4 Experiment protocol

Two carboys with working volume of 20L were used as digesters; one served as the control digester and the other one as the test digester. The control digester was fed only with feed sludge, while the test digester received feed sludge along with restaurant grease. The temperature of the two digesters was controlled at 37±1 °C by a water bath heated with an immersion heater. The schematic of the experiment setup is shown in Figure 3-1.

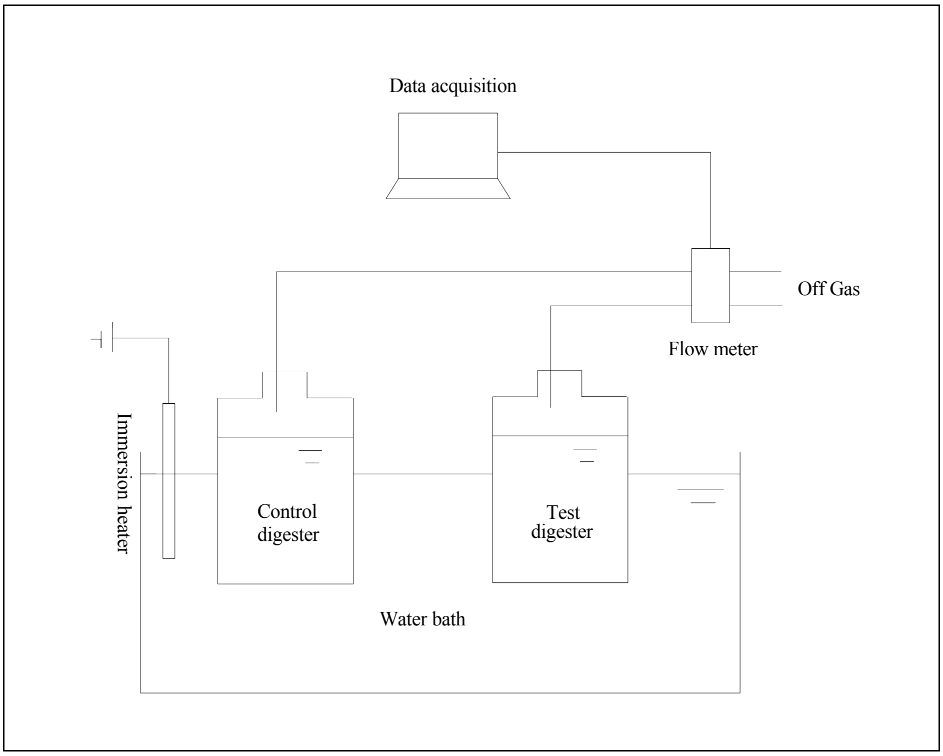

Figure 3- 1 Schematic of the experiment setup

3.4.1 Experiment outline

Digester loading was based on total chemical oxygen demand (COD) of the feed stocks. Therefore, the amount of restaurant grease added was based on the COD of feed sludge. The whole experiment was divided into four stages in terms of COD loading of the digesters.

1) Baseline setup: The aim of this stage was to assess the equivalence of the performance of the two digesters. The two digesters received the same feed in

this stage. They were started up by seeding with 19 L seed sludge along with 1L feed sludge in the first day of operation. After that, 1L digested sludge was removed from each of the two digesters and 1L fresh feed sludge was added every day until the steady state had been reached.

To evaluate the digestion process for the two digesters, two situations are introduced: steady state and upset conditions. Steady state was considered to be achieved when biogas production, pH and alkalinity data collected over a continuous 5-day period lay within two standard deviations of the corresponding mean values. Upset conditions would emerge in the event that either pH dropped below 6.8 or PA decreased below 1000 mg/L (Reynolds and Richards, 1995; WEF, 2007). Meanwhile, a drop in biogas production could indicate upset conditions as well.

2) COD loading of 130%: After the baseline of the two digesters was established, the COD loading of the control digester was maintained, while the COD loading of the test digester was elevated to 120% compared to the loading of the control digester. The test digester was not only fed with the same amount of feed sludge as the control digester but also with a certain amount of restaurant grease, which contributed the 20% loading increase. The loading kept on increasing at 5% increments up to the loading of 130%. At each increment, the loading was maintained for 5 days before the next step increase. At the loading of 130%, when steady state was reached, 10-day continuous sampling and testing was conducted.

3) COD loading of 160%: After 10-day sampling was performed at the loading of 130%, the loading continued increasing at 10% increments up to the loading of 160%. At each increment, the loading was maintained for 5 days before the next step increase. At the loading of 160%, when steady state was reached, 10-day continuous sampling and testing was conducted.

4) Upper limit loading exploration: After 10-day sampling was performed at the loading of 160%, the loading was increased at 10% increments up to the loading of 190%. Later on, the increment was raised to 20% until the loading reached 300%. There were no upset conditions observed up to 300%. Therefore, the increment was subsequently raised to 50%. Eventually, the experiment ended up with the loading of 400%. After steady state was reached, 5-day continuous sampling and testing was conducted. If the test digester exhibited the upset conditions, the loading would be reduced to the loading where stable operation was last observed. However, this situation did not occur in the experiment.

3.4.2 Digester operation

The two digesters were operated at an HRT of 20 days and were renewed once a day for about 9 months. However, because of the addition of restaurant grease, the effective HRT for the test digester was slightly reduced. Table B-1 in Appendix B shows the theoretical feed regime assuming that TCOD of feed sludge is 50 g/L and TCOD of restaurant grease is 1720 g/L. The TCOD values adopted here are based on the real TCOD test. In fact, restaurant grease feed volumes and resulting test digester HRT values would slightly change depending on the actual TCOD values at the particular operation stage. From Table B-1, it can be seen even at the maximum loading, the test digester HRT, 18.2 d, is close to the control digester HRT, 20 d.

In addition, the essential and detailed operating conditions for the test digester at the loading of 160% and 387% are presented in Table 3-5 and Table 3-6, respectively.

Table 3- 4 Test digester operating conditions at the loading of 130%

Digester Conditions		
Temperature	37±1	°C
Working volume	20	L
Sludge Fed	1000	mL/day
Grease Fed	7.6	mL/day
Test digester HRT	19.85	days
COD of Sludge	44,438	mg COD/L
COD of Grease	1,747,015	mg COD/L
COD from Sludge	44,438	mg COD/day
COD from Grease	13,331	mg COD/day
Total COD added	57,769	mg COD/day
COD loading from Sludge	2,222	mg COD/(day·L)
COD loading from Grease	667	mg COD/(day·L)
Total COD loading	2,888	mg COD/(day·L)
% COD Increase	**30%**	
VS of Sludge	25,443	mg VS/L
VS of Grease	652,227	mg VS/L
VS from Sludge	25,443	mg VS/day
VS from Grease	4,977	mg VS/day
Total VS added	30,420	mg VS/day
VS loading from Sludge	1,272	mg VS/(day·L)
VS loading from Grease	249	mg VS/(day·L)
Total VS loading	1,521	mg VS/(day·L)
% VS increase	**20%**	

Table 3- 5 Test digester operating conditions at the loading of 160%

Digester Conditions		
Temperature	37±1	°C
Working volume	20	L
Sludge Fed	1000	mL/day
Grease Fed	17.0	mL/day
Test digester HRT	19.7	days
COD of Sludge	48,825	mg COD/L
COD of Grease	1,722,501	mg COD/L
COD from Sludge	48,825	mg COD/day
COD from Grease	29,295	mg COD/day
Total COD added	78,120	mg COD/day
COD loading from Sludge	2,441	mg COD/(day·L)
COD loading from Grease	1,465	mg COD/(day·L)
Total COD loading	3,906	mg COD/(day·L)
% COD Increase	**60%**	
VS of Sludge	27,475	mg VS/L
VS of Grease	655,367	mg VS/L
VS from Sludge	27,475	mg VS/day
VS from Grease	11,146	mg VS/day
Total VS added	38,621	mg VS/(day·L)
VS loading from Sludge	1,374	mg VS/(day·L)
VS loading from Grease	557	mg VS/(day·L)
Total VS loading	1,931	mg VS/(day·L)
% VS increase	**41%**	

Table 3- 6 Test digester operating conditions at the loading of 387%

Digester Conditions		
Temperature	37±1	°C
Working volume	20	L
Sludge Fed	1000	mL/day
Grease Fed	88.2	mL/day
Test digester HRT	18.378974	days
COD of Sludge	53,500	mg COD/L
COD of Grease	1,743,750	mg COD/L
COD from Sludge	53,500	mg COD/day
COD from Grease	153,799	mg COD/day
Total COD added	207,299	mg COD/day
COD loading from Sludge	2,675	mg COD/(day·L)
COD loading from Grease	7,690	mg COD/(day·L)
Total COD loading	10,365	mg COD/(day·L)
% COD Increase	**287%**	
VS of Sludge	27,013	mg VS/L
VS of Grease	654,136	mg VS/L
VS from sludge	27,013	mg VS/day
VS from Grease	57,695	mg VS/day
Total VS added	84,708	mg VS/(day·L)
VS loading from Sludge	1,351	mg VS/(day·L)
VS loading from Grease	2884.739	mg VS/(day·L)
Total VS loading	4,235	mg VS/(day·L)
% VS increase	**214%**	

Daily routine for renewing the digesters included the following steps:

1) Stop the data acquisition software of the digital gas flow meter

2) Shake the digesters thoroughly

3) Unscrew the caps on top of the digesters

4) Withdraw appropriate amount of digested sludge via a narrow scoop inserted from the top of the carboys

5) Add new feed sludge from the top of both digesters

6) Add restaurant grease to the test digester

7) Screw the caps back onto the digesters

8) Flush the digesters with N_2 for one minute

9) Shake the digesters thoroughly

10) Start the data acquisition software of the digital gas flow meter

The temperature was monitored once every day by measuring the digested sludge. The range of temperature fluctuation was between 36 °C to 38 °C. If any deviation from 37 °C was observed, the immersion heaters would be correspondingly adjusted. The pH values of the digesters were monitored daily, and no adjustment was ever needed.

The feeding process would take about 30 minutes per day. For the rest of the time, the biogas production for the two digesters was monitored by a 2-chamber flow meter at the same time. This flow meter works on the principle of pressure differentials, and requires 3" ~ 4" water column pressure in the digesters being monitored. Compared to the ambient pressure, 3" ~ 4" water column pressure (approximately 1 kPa) is relatively small and can be neglected. Therefore, the headspace pressure in the digesters is considered to be equal to the ambient pressure, which was monitored daily by a barometer.

The biogas production data were automatically output to a computer and recorded every 10 minutes. It would take about 5~15 minutes after the caps were screwed back onto the carboys after feeding before the headspace pressure increased enough for biogas production to resume registering on the meter.

3.4.3 Sampling plans

In different stages of digester operation, different sampling schedules were adopted. Before the steady state was reached, digester performance was monitored according to the schedule given in Table 3-7.

Table 3- 7 Sampling schedule prior to the steady state

Parameter	Feed sludge	RG	Digested sludge	Digester gas
pH	Once per batch	Once per batch	Daily	--
Alkalinity	--	--	Daily	--
% CO_2	--	--	--	Every 2 days
Biogas production	--	--	--	Continuously
TS	5-day composite	Once per batch	5-day composite	--
VS	5-day composite	Once per batch	5-day composite	--
TCOD	5-day composite	Once per batch	5-day composite	--

When steady-state operation was observed in the test digester, more intensive sampling was conducted during a 10 day or 5 day sampling period. Table 3-8 shows the detailed sampling schedule for steady state. This sampling schedule was applied to the test digester. However, for the control digester, all the parameters were monitored three times during a 10 day or 5 day sampling period.

Table 3- 8 Sampling schedule at the steady state

Parameter	Feed sludge	RG	Digested sludge	Digester gas
pH	Once per batch	Once per batch	Daily	--
Alkalinity	--	--	Daily	--
Biogas production	--	--	--	Continuously
% CH_4	--	--	--	Every 2 days
% CO_2	--	--	--	Every 2 days
TS	Once per batch	Once per batch	Daily	--
VS	Once per batch	Once per batch	Daily	--
TCOD and SCOD	Once per batch	Once per batch	Daily	--
Volatile Acids	--	--	Every 3 days	--

3.4.4 Sample analyses

pH and alkalinity were tested right away after the samples were taken. COD and solids content analyses were performed within 72 hours and samples were stored at 4 °C. Volatile acids were generally measured on the day of collection. If the measurement could not be performed on the same day, samples would be stored at 4 °C as well. GC tests for methane and carbon dioxide were conducted once a week and gas samples were taken into quality sample bags and stored at room temperature and pressure.

COD and solids content were tested in triplicate. Alkalinity was tested in duplicate. The other measurements were performed once per sample.

pH, solids content, methane and carbon dioxide were analyzed directly. To obtain TCOD, samples were diluted with distilled water to according to the upper limit of COD test and the COD of samples. Samples needed centrifuging prior to alkalinity, SCOD and volatile acids analyses. For alkalinity, samples were centrifuged at a centrifugal force of 1018×g for 10 minutes. For SCOD and volatile acids, samples were centrifuged at a centrifugal force of 4075×g for 15 minutes. The supernatants obtained after centrifugation could be used to test alkalinity directly. For SCOD, the supernatants were filtered through 0.45μm filters and the filtrate was analyzed. For volatile acids, the supernatants were filtered through 0.22μm filters and the filtrate was analyzed.

4.0 Results and Discussion

4.1 Wastes characterization

Fresh feed sludge from Goldbar WWTP was obtained once a month. Its characteristics varied during the eight-month experimental period (see Table 4-1). During the 100% COD loading period, the strength of feed sludge was much higher than that of other periods. In other periods, TS varied greatly, but COD and VS fluctuated little and showed the same trends. RG exhibited relatively stable characteristics and almost 100% of RG was volatile solids. In addition, the solids content of fresh feed sludge ranged from 4.9% to 5.8%.

Table 4- 1 Characteristics of feed sludge and restaurant grease

COD loading period	Feed sludge				Restaurant Grease			
	COD (g/L)	TS (g/L)	VS (g/L)	VS/TS (%)	COD (g/L)	TS (g/L)	VS (g/L)	VS/TS (%)
100%	69.9±2.9[a]	55.2±2.3	39.5±1.9	71.5	n/a	n/a	n/a	n/a
130%	43.5±1.4	33.0±1.0	24.7±0.8	74.8	1747.0±2.5	654.0±3.0	652.2±3.0	99.7
160%	49.1±1.0	48.0±0.4	26.7±0.6	55.6	1722.5±16.3	657.2±3.4	655.4±3.4	99.7
387%	53.5±0.4	39.1±0.6	27.0±0.6	69.1	1743.0±16.5	656.1±19.4	654.1±19.4	99.7

[a] The values are expressed in the form of Mean ± Standard deviation

4.2 Baseline setup

Baseline setup in this experiment took approximately 40 days, which equalled to about two HRTs. One or two HRTs are usually suggested for start-up period (Bjornsson et al., 2000).

Continuous 5-day sampling and measurement were conducted at the end of this stage to demonstrate steady state and compare the performance of control and test digesters.

In addition, gas production data used in this paper were all converted into standard conditions, i.e. pressure 101.325 kPa and temperature 273.15 K.

4.2.1 Demonstration of steady state

As stated in Section 3.4.1, the criterion used for testing steady state is that continuous 5-day data of biogas production, pH and alkalinity lie within two standard deviations of the corresponding mean values. According to Standard Methods (2005), it is sufficiently accurate to state that 95% of the values are within in this range.

Figure 4-1, 4-2 and 4-3 depict daily biogas production, pH, PA and TA data from April 04, 2010 to April 08, 2010. From these figures, it can be clearly observed that all the data fluctuated within the range of two standard deviations from the mean. There was no outlier for any of the four parameters. Hence, steady state was considered to be achieved during that period.

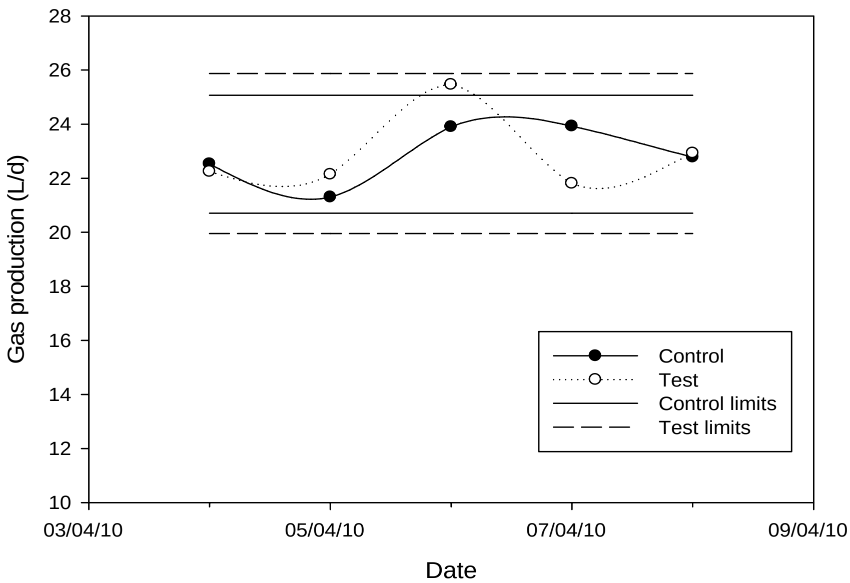

Figure 4- 1 Daily biogas production for control and test digesters

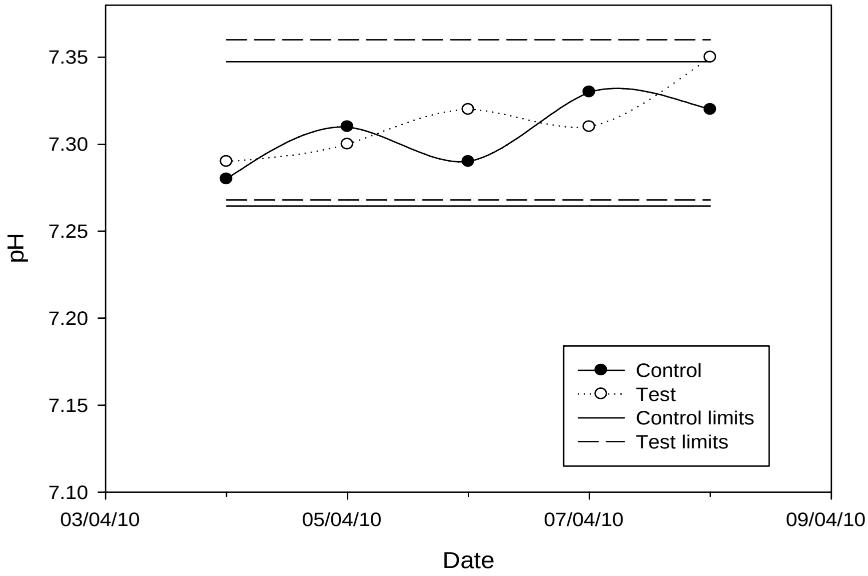

Figure 4- 2 pH values for control and test digesters

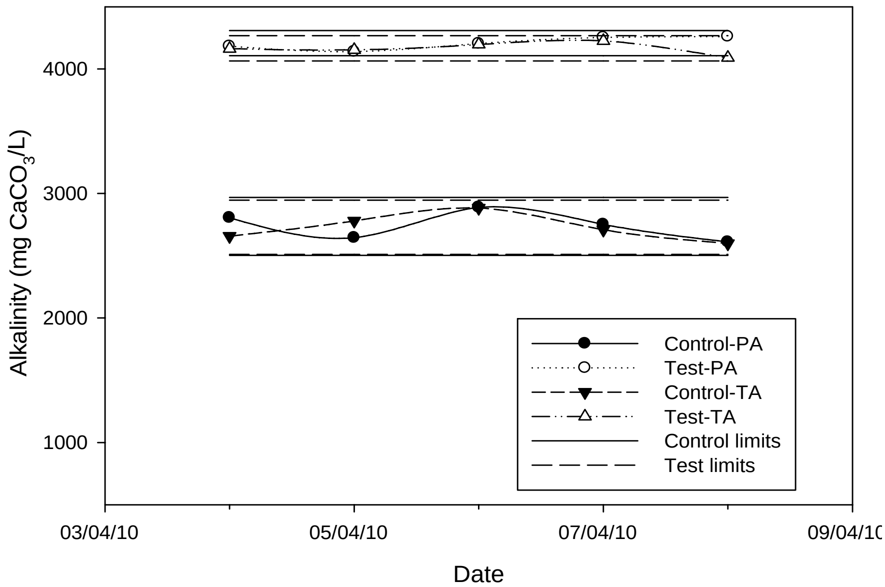

Figure 4- 3 PA and TA values for control and test digesters

4.2.2 Comparison between control and test digesters

The aims of this stage were not only to achieve steady state in two digesters but also to obtain equivalent performance in the two digesters. To fully evaluate digestion performance, besides the four parameters mentioned above, COD, VS and TS were also measured when the digesters reached steady state. The mean values of all the seven parameters during this sampling period are listed in Table 4-2. Furthermore, for each parameter, the difference between the two digesters is presented by percentage and listed in Table 4-2 as well. The difference is calculated in the following equation.

$$\text{Difference}\,(\%) = \frac{\text{Control digester value} - \text{Test digester value}}{\text{Mean of control and test digester values}} \times 100\%$$

Negative values mean the value of this parameter for test digester is higher than that for control digester. The absolute values of the difference for all seven parameters were lower than 2%. Additionally, COD reduction for control and test digesters were 61.9% and 62.5%, respectively; VS reduction for control and test digesters were 60.6% and 61.2%, respectively. Slight differences between the seven monitored parameters as well as similar COD and VS reduction indicated the performance of the two digesters were equivalent and baseline had been established.

Table 4- 2 Comparison of digester performance in terms of seven parameters

Parameters	Control	Test	Difference between two digesters
Daily biogas production (L/d)	22.89±1.09[a]	22.91±1.48	-0.1%
pH	7.31±0.02	7.31±0.02	-0.1%
PA (mg $CaCO_3$/L)	2740±114	2725±50	0.5%
TA (mg $CaCO_3$/L)	4208±50	4166±51	1.0%
Effluent COD (g/L)	26.6±0.8	26.2±0.8	1.6%
Effluent TS (g/L)	28.2±1.0	27.8±0.6	1.4%
Effluent VS (g/L)	15.5±0.6	15.3±0.4	1.5%

[a] The values are expressed in the form of Mean ± Standard deviation

4.3 Digestion process monitoring

Digestion process for control and test digesters was monitored in terms of pH, PA, TA, VFAs and CO_2 content in biogas during different COD loading periods. For the control digester, it was merely fed feed sludge and thus its COD loading was set as a baseline for test digester. For the test digester, besides feed sludge, RG was added. Therefore, its COD loading increased continuously and was expressed as a percentage of the COD loading to the control digester at anytime. Steady states were reached in COD loading of 130%, 160% and 387%. Other COD loadings were maintained for 3 to 5 days and the performance might not become stable during these periods. The average of each parameter was used as the indicator for each COD loading period in the following analysis.

4.3.1 pH

pH values for both control and test digesters throughout the experiment are illustrated in Figure 4-4. pH values for control digester remained within 7.25 to 7.40, which was normal and suitable pH range for anaerobic digestion. For test digester, pH values kept declining with COD loading increase and went down to 7.09 in the highest COD loading of 387%. Analysis of variance (ANOVA) for pH values at different loading periods was conducted separately at a significance level of 0.05 (results are presented in Appendix D). The results indicated that before COD loading reached 170%, pH values for the two digesters were in the same level and the discrepancy between the two digesters was not significant compared with normal pH variation in an individual digester. After COD loading reached 170%, the discrepancy between the two digesters became more and more remarkable. Especially, when COD loading went beyond 250%, pH values for the test digester dropped dramatically. In other words, pH was able to respond to additional loading increases after COD loading increased to 170% in this codigestion process.

In fact, pH is a widely accepted parameter for monitoring the digestion process. According to pH, the lower limit for normal digestion operation is 6.8 (Bjornsson et al., 2000; WEF, 2007). Codigestion was feasibly conducted in COD loading of 387% with a pH of 7.09 and overloading was not reached. It was possible to go on elevating the loading. However, it was not far from overloading, as pH 6.8 was near.

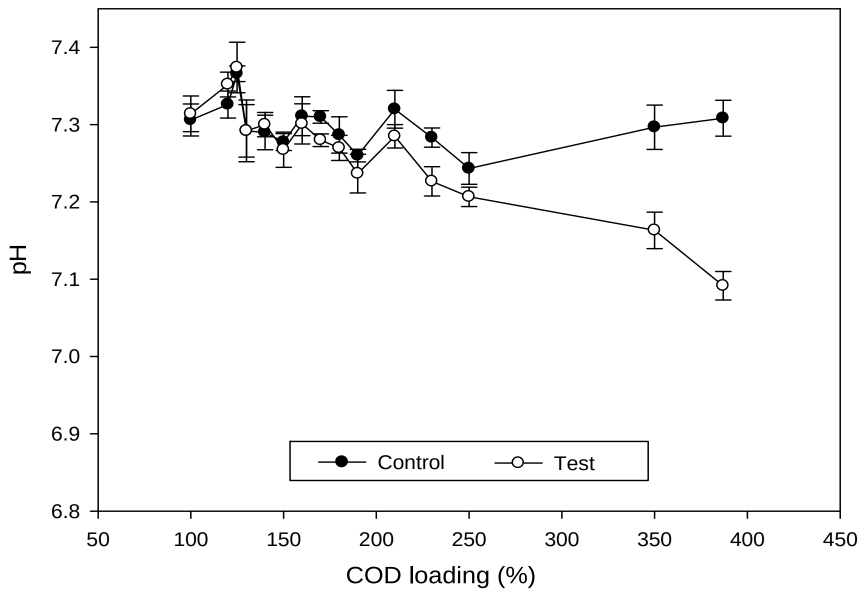

Figure 4- 4 pH values for control and test digesters during different COD loading periods

4.3.2 PA and TA

Since the strength of the feed sludge became weaker after the period of 140% COD loading, a sudden drop was observed in PA and TA for both digesters

(Figure 4-5). Later on, the strength of the feed sludge was relatively stable. So, for the control digester, PA remained steady at about 2200 mg/L, and there was a slow increase for TA, up to about 4010 mg/L. For the test digester, the minimum PA and TA values were 1496 mg/L and 2788 mg/L, respectively, during the period of 387% COD loading. For normal operation, alkalinity concentrations under mesophilic anaerobic digestion range from 1000 mg/L and 5000 mg/L (Reynolds and Richards, 1995; WEF, 2007). All the PA and TA values measured in this experiment were in this range. Thus, upset conditions were not observed throughout this codigestion in terms of alkalinity. However, the minimum PA was already close to the lower limit.

ANOVA was applied to PA and TA data at 130% COD loading period at a significance level of 0.05 (results are presented in Appendix D). As for PA, prior to COD loading of 130%, the difference between the two digesters was small. This difference increased as the loading increased, which was similar to the change of pH. As for TA, the same tendency with PA can be observed. In addition, it can be shown from Figure 4-5 that the negative slopes for PA and TA were generally identical, which indicates that the sensitivity for PA and TA to loading increase was similar. Overall, after COD loading of 130%, PA and TA were able to reflect loading increase in this codigestion process.

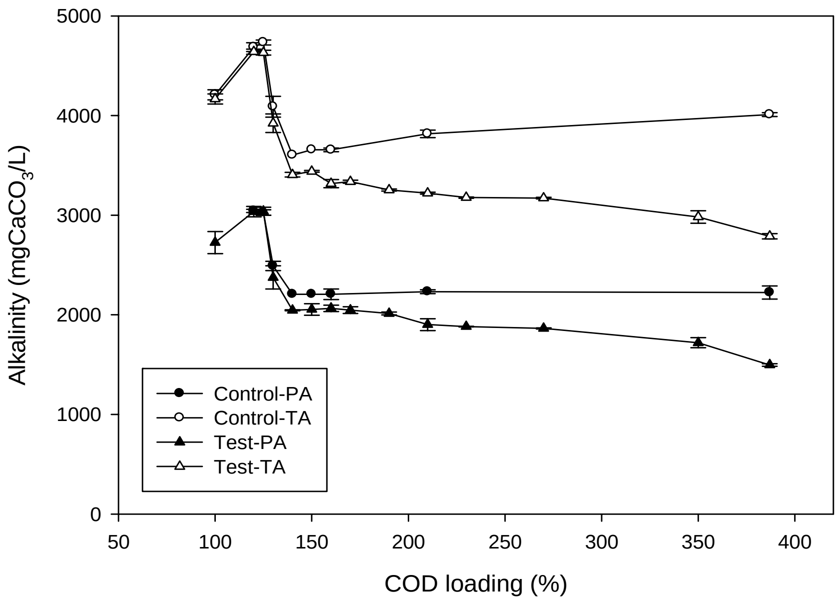

Figure 4- 5 PA and TA values for control and test digesters during different COD loading periods

4.3.3 CO_2 contents

As shown in Figure 4-6, CO_2 contents of control digester biogas stayed quite constant within the range of 30.4% to 32%. CO_2 content for test digester biogas showed a slightly decreasing trend, however, it fluctuated up and down within the range of 26.9% to 29.3%. The distinction of CO_2 content between the two digesters can be observed after COD loading reached 160%. The normal range for CO_2 content is from 25% to 35% (Reynolds and Richards, 1995; WEF, 2007). So, from the perspective of CO_2 content, both digesters were under normal operation. As with pH and alkalinity, CO_2 content at the highest COD loading was close to the lower limit.

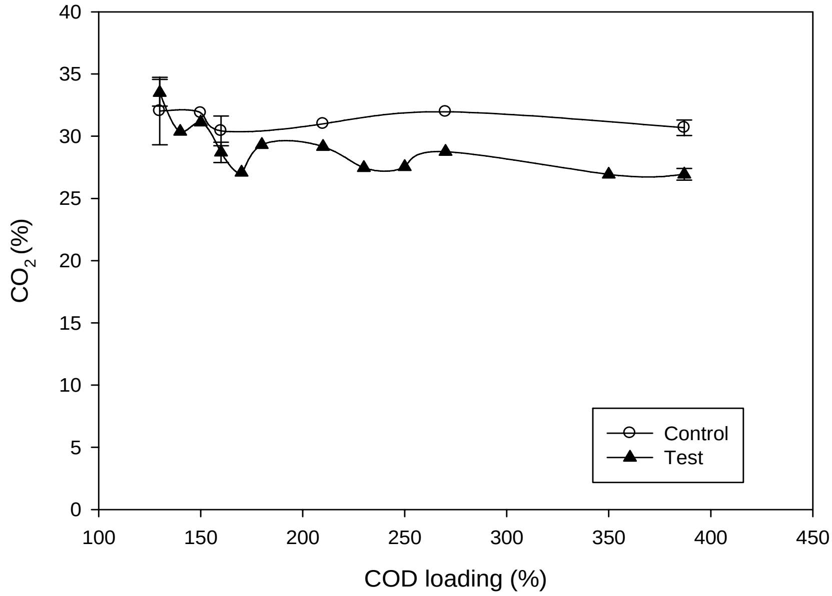

Figure 4- 6 CO_2 contents for control and test digesters during different COD loading periods

4.3.4 VFAs

VFAs were usually tested when the digesters were operating at steady state and one more test for test digester was conducted in COD loading of 250%. The results are presented in Table 4-3. Only acetic acid could be quantified. Propionic acid, *iso*-butyric acid and *n*-butyric acid could be detected in both digesters, but their concentrations were below quantification limits (1-20mg/L) in this experiment. *Iso*-valeric acid and *n*-valeric acid were not detected. Acetic acid concentration rose steadily with the increase of COD loading. However, even the highest concentration only reached 65 mg/L, which was still in the low level of the range 50 to 250 mg/L for normal operation (Reynolds and Richards, 1995; WEF, 2007). Luostarinen et al. (2009) reported a peak value of 430 mg/L under highest grease trap sludge addition (71% of feed VS loading), while less than 120 mg/L were detected in the control digester. Bjornsson et al. (2000) also found

VFAs concentration was very low, below 5 mg/L, under the OLR of 1.6 kg VS/ (m^3·d) when digesting MSW alone.

Table 4- 3 Acetic acid concentration during different COD loading periods

COD loading	Acetic acid concentration (mg/L)	
	Control	Test
100%	≤ 10	≤ 10
130%	≤ 10	≤ 10
160%	≤ 10	15
250%	--	37
387%	--	65

In recent years, VFAs have been considered by many researchers to be an efficient and sensitive indicator for monitoring digestion processes (Bjornsson et al., 2000). But VFAs concentration in different digestion systems varied greatly. Approximately 2000 mg/L was considered as the maximum value by Reynolds and Richards (1995). In the case of codigestion of the organic fraction of municipal solid waste with FOG, VFAs rose to about 2100 mg/L during start-up period and dropped below 500 mg/L when steady state was reached (Martin-Gonzalez et al., 2010).

4.3.5 Parameter comparison

pH, PA, TA, CO_2 content, and VFAs were able to respond to loading increase in this codigestion process. Nevertheless, their performance for reflecting the loading increase varied. In terms of response speed, among these parameters, PA and TA showed the fastest response to the loading increase, starting from COD loading of 140%. From the aspect of predicting overloading, pH, PA and CO_2 content approached to the lower limits of normal operation, however, CO_2

content wavered greatly resulting in that the tendency was not clear. VFA concentrations in this system were relatively low and were not very helpful for indicating overloading and identifying the occurrence of system upset. PA proved to be a more sensitive monitoring parameter whereas pH and TA also functioned well as monitoring parameters. PA and pH should be considered together to monitor digestion processes, which was also suggested by Bjornsson et al. (2000).

4.4 Evaluation of digestion performance

The main purpose of addition of RG is to enhance the digestion performance, characterized by increased biogas production, higher methane yields, and higher COD or VS reduction. Daily biogas production data were collected and then were averaged according to different COD loading periods. The average of daily biogas production was used to represent the biogas production during each COD loading period. Similarly, COD, VS, and methane content values were also averaged in terms of different COD loading periods. Further, methane yields, COD and VS reduction were calculated based on the corresponding average values.

The organic loading for digesters can be presented on COD and VS basis. For easy comparison with other research, commonly used expressions for organic loading and their applications in this experiment are summarized in Table 4-4.

Table 4- 4 Characterizations of organic loading during different COD loading periods

COD loading period	OLR[a] kgCOD/m^3/d		OLR kgVS/m^3/d		RG content of feed wastes		Increase % of test digester over control digester	
	Control	Test	Control	Test	COD	VS	COD loading	VS loading
130%	2.222	2.888	1.272	1.521	23%	17%	30%	20%
160%	2.441	3.906	1.374	1.931	37%	29%	60%	42%
387%	2.675	10.365	1.351	4.235	74%	68%	287%	214%

[a] OLR=organic loading rate

4.4.1 Daily biogas production

Compared to control digester, daily biogas production from test digester increased considerably with the gradual increasing addition of RG (Figure 4-7). There was no reduction of biogas production throughout this experiment, which indicated overloading was not reached. This was in agreement with the observations from pH, PA, TA and CO_2 content. With the highest RG addition, increase in COD loading by 287% (VS loading by 214%) led to daily biogas production increase by 467%, compared to that of the control digester. Meantime, as shown in Figure 4-7, a linear correlation between COD loading (%) and daily biogas production increase (%) was observed with R^2=0.994. The linear relationship showed that up to the highest loading in this experiment there was no negative effect on biogas production and no methanogenic inhibition.

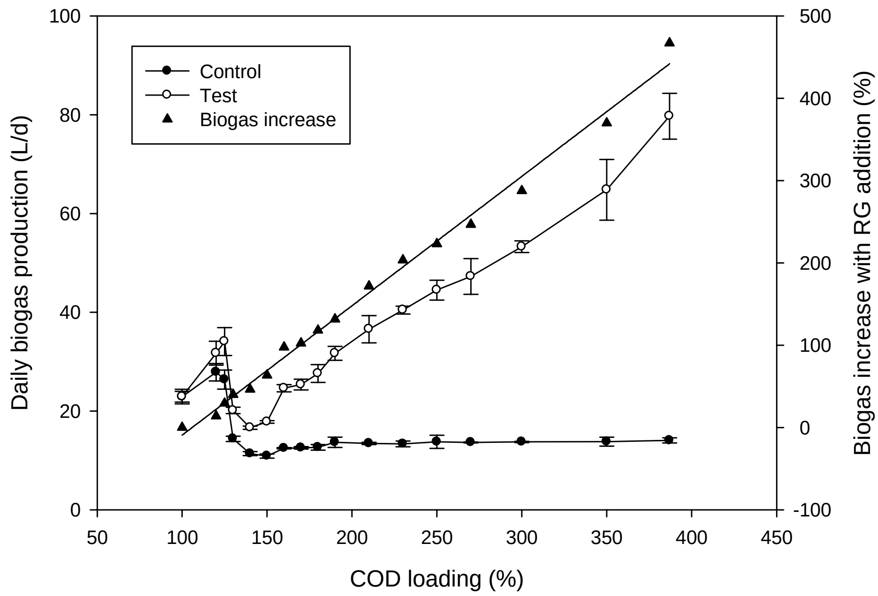

Figure 4- 7 Daily biogas production for control and test digesters during different COD loading periods

4.4.2 COD and VS reduction

Steady states were reached in COD loading of 130%, 160% and 387%. COD and VS reduction and methane yields were calculated during these three COD loading periods.

Tables 4-5 and 4-6 list the results of COD reduction and VS reduction, respectively. For the control digester, COD and VS reduction were relatively stable. For the test digester, COD and VS reduction showed the same increasing tendencies with increased loading. In the period of 387% COD loading, COD and VS reduction for the test digester were 29.8% and 27.2% greater than those for the control digester, respectively. However, the remaining COD and VS in the effluents increased as well. This may result from the increased concentration of microorganisms or the residual RG which was incompletely degraded. Similar results were also obtained by Luostarinen et al. (2009). At higher grease trap sludge additions, VS reductions were higher and the remaining VS in effluent were higher as well (Luostarinen et al., 2009).

Table 4- 5 Results of effluent COD values and COD reduction for control and test digesters during different COD loading periods

COD loading period	COD (g/L)			RG addition		COD reduction	
	Feed sludge	C[a]-Effluent	T[b]-Effluent	V(L)	gCOD /d	Control	Test
130%	43.5±1.4[c]	22.7±2.1	25.1±0.8	0.0076	13.0	47.8%	55.3%
160%	49.1±1.1	24.1±1.1	27.6±0.3	0.0170	29.3	50.9%	64.2%
387%	53.5±0.4	28.1±0.1	43.2±1.5	0.0882	153.8	47.5%	77.3%

[a] Control digester
[b] Test digester
[c] The values are expressed in the form of Mean ± Standard deviation

Table 4- 6 Results of effluent VS values and VS reduction for control and test digesters during different COD loading periods

COD loading period	VS (g/L)			RG addition		VS reduction	
	Feed sludge	C[a]-Effluent	T[b]-Effluent	V(L)	gVS/d	Control	Test
130%	24.7±0.8[c]	13.8±0.7	15.3±0.6	0.0076	5.0	44.4%	48.0%
160%	26.7±0.6	13.8±0.5	15.7±0.3	0.0170	11.1	48.3%	57.6%
387%	27.0±0.6	14.8±1.2	21.3±0.4	0.0882	57.7	45.4%	72.6%

[a] Control digester
[b] Test digester
[c] The values are expressed in the form of Mean ± Standard deviation

4.4.3 Methane contents and methane yields

According to ANOVA at a significance level of 0.05 (results are presented in Appendix D), there was no difference in CH_4 contents between the control digester and the test digester at 130% COD loading period. At the other two periods, CH_4 contents in the test digester were greater than that in the control digester. As seen from Table 4-7, RG addition resulted in slight increase of CH_4 contents. This was consistent with other codigestion experiments using FOG (Kabouris et al. 2008; Davdisson et al. 2008).

The reason may be the carbon in fats has lower (more negative) mean oxidation state than that in sludge (Gujer and Zehnder, 1983). Theoretically, carbon in methane has negative oxidation state and carbon in carbon dioxide has positive oxidation state. Furthermore, gained electrons when organic matters are reduced to methane are less than lost electrons when organic matters are oxidized to carbon dioxide. Therefore, the lower mean oxidation states of carbon in degraded organic matters are, the more methane is produced (Gujer and Zehnder, 1983).

Table 4- 7 CH_4 contents for control and test digesters during different COD loading periods

COD loading period	CH_4 content		Difference[c]
	C[a]	T[b]	
130%	65.3%	66.2%	1.3%
160%	60.3%	62.6%	3.8%
387%	59.5%	65.8%	10.7%

[a] Control digester
[b] Test digester
[c] Difference = (Test digester value – Control digester value)/Control digester value

Methane yields are presented based on both COD and VS. Meanwhile, two types of methane yields are introduced. One is calculated from COD or VS reduction, the other one is from COD or VS feed.

Theoretical value for methane yield based on COD reduction is 0.35 m^3 CH_4 / kg COD reduction (Metcalf & Eddy, 2003). Seen from Table 4-8, the methane yields obtained in the experiment were close to this value except for the yields during the period of COD loading of 130%, which for both control and test digester were slightly higher than theoretical value.

Typically accepted range for biogas yields based on VS reduction is from 0.75 to 1.12 m^3/ kg VS reduction (Metcalf & Eddy, 2003). Combining with the typical range (55% to 75%) of methane contents in biogas (Reynolds and Richards, 1995), the VS reduction yield range can be converted into 0.34 - 0.84 m^3 CH_4 / kg VS reduction. As shown in Table 4-9, most methane yields agreed well with the accepted range, except for the yields during the period of COD loading of 130%. This was in accordance with methane yields based on COD reduction.

In terms of methane yields based on COD reduction, there was little difference between control and test digesters. Whereas, methane yields based on VS reduction were enhanced with the addition of RG, suggesting a possible synergy effect. In terms of methane yields based on COD and VS feed, codigestion with RG led to great increase in these two types of methane yields. This is because with the loading increase, the portions of RG in feed COD and VS increase and RG has higher methane potential than MWS.

Table 4- 8 CH_4 yields based on COD for control and test digesters during different COD loading periods

COD loading period	CH_4 yield based on COD					
	m^3 CH_4 / kg COD reduction			m^3 CH_4 /kg COD feed		
	Control	Test	Difference[a]	Control	Test	Difference[a]
130%	0.451	0.426	-5.5%	0.216	0.235	8.8%
160%	0.301	0.306	1.7%	0.153	0.197	28.8%
387%	0.329	0.327	-0.6%	0.156	0.253	62.2%

a Difference = (Test value – Control value)/Control value

Table 4- 9 CH_4 yields based on VS for control and test digesters during different COD loading periods

COD loading period	CH_4 yield based on VS					
	m^3 CH_4 / kg VS reduction			m^3 CH_4 /kg VS feed		
	Control	Test	Difference[a]	Control	Test	Difference[a]
130%	0.857	0.935	9.1%	0.380	0.448	18.0%
160%	0.584	0.709	21.4%	0.282	0.408	44.9%
387%	0.682	0.853	25.2%	0.309	0.620	100.2%

a Difference = (Test value – Control value)/Control value

Table 4-10 collected some results from similar studies. When similar grease content (30%) was applied, the results of methane yield, VS reduction and methane content were quite comparable with those from the current study. Compared to other research, grease content in the current study was applied to the highest proportion (68%) without adverse effect on digestion performance. 71% grease content was tried by Loustarinen et al. (2009), but methane production and content decreased.

Table 4- 10 Comparison of results from present study and other research

HRT (day)	OLR (kgVS/m^3)	Grease content in feed VS (%)	Methane yield (m^3 CH_4 /kg VS feed)	VS Reduction (%)	CH_4 (%)	Source
12	4.35	48	0.449	45	66	Kabouris et al. 2009b
16	2.8	28	0.444	52	61	Loustarinen et al. 2009
16	3.46	46	0.463	67	65	Loustarinen et al. 2009
16	4.41	71	0.315	70	58	Loustarinen et al. 2009
13	2.40	30	0.344	58	69	Davdisson et al. 2008
19.8	1.52	17	0.448	48	66	Current results
19.7	1.93	29	0.408	58	63	Current results
18.5	4.24	68	0.620	73	66	Current results

5.0 Conclusion and Recommendation

5.1 Conclusion

The following conclusions can be summarized from this anaerobic codigestion study.

1) Anaerobic codigestion of municipal wastewater sludge and restaurant grease was successfully performed in 20L lab-scale digesters operated semi-continuously at 37 °C.

2) In the loading range of this study, loading increase could be reflected by the decrease of pH, PA, TA and CO_2 content, and the increase of VFAs. Among the five monitored parameters, PA was the most sensitive and responded to the loading increase from COD loading of 140% by exhibiting obvious decreasing tendency.

3) PA and pH were suggested to be considered together to monitor digestion process and predict overloading.

4) Codigestion of municipal wastewater sludge and restaurant grease was feasible up to 387% of the control digester COD loading (i.e. OLR=4.235 kgVS/m^3/d). Compared to the control digester, this loading rate increased daily biogas production by 467%, methane yield by 25.2% (based on VS deduction), COD reduction by 29.8% and VS reduction by 27.2%, respectively. Methane yield based on COD reduction maintained steady. No negative effect of grease addition was observed on digestion performance.

5) With grease addition, methane content in test digester increased slightly in comparison with that in control digester, fluctuating from about 62% to 67%.

5.2 Recommendation

Based on the current study, the following recommendations are proposed for future investigation:

1) Although the test digester approached overloading in this study, it is possible to keep increasing organic loading rate; however, the increment should be slowed down.

2) Operation stages based on COD loading could be adjusted. In the stage of 130% COD loading, the difference between control and test digester was not so obvious. Therefore, this stage could be replaced by another stage of which COD loading is between 160% and 387%.

3) Considering acclimation, in the beginning of grease addition, 5% increment with 5-day maintenance period is recommended. 130% COD loading could be adopted as the initial loading. After COD loading of 160%, the increment could be enlarged to 20%. When the digestion process is close to overloading, the increment could be slowed down to 5% or 10%.

4) VFAs analysis could be improved by using suitable gas chromatography. Efforts should be made to measure the major VFAs: acetic acid, propionic acid and butyric acid.

5) Identification of maximum loading rate should take both digestion capacity and effluent COD into account.

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7.0 Appendices

Appendix A Analytical methods

A.1 Gas chromatography for methane and carbon dioxide

Methane and carbon dioxide content of biogas were analyzed simultaneously by a gas chromatography unit (Shlmadzu GC-8A) equipped with a thermal conductivity detector. The column is HayesepQ 80/100, with 6' length and 1/8" diameter. Inject port temperature is 120 °C, and detector temperature is 120 °C, and column temperature is 35 °C. Carrier gas is Helium with flow rate of 30 mL/min.

The calibration curves for methane and carbon dioxide are shown in Figures A-1 and A-2, respectively.

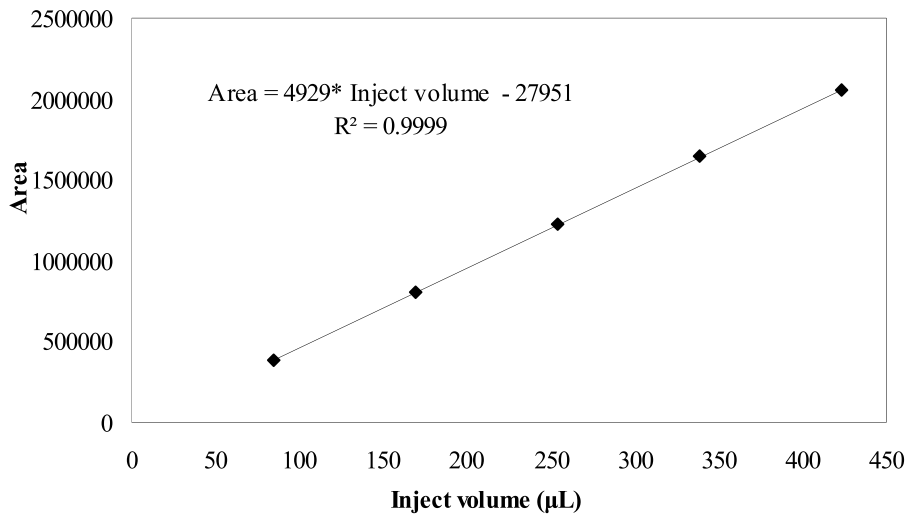

Figure A- 1 Calibration curve for methane content analysis

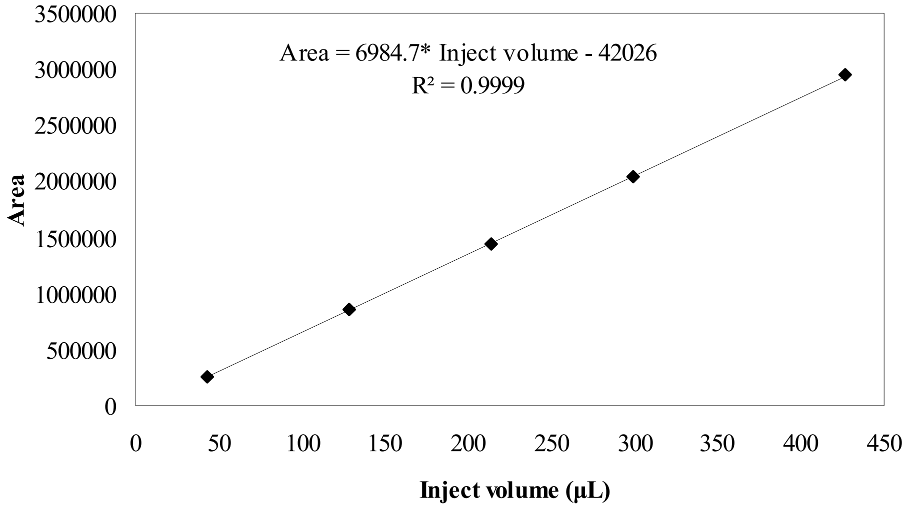

Figure A- 2 Calibration curve for carbon dioxide content analysis

A.2 Ion chromatography for volatile acids

Measurement of volatile acids was performed ion chromatographically with a conductivity detector (Dionex) and IonPas AS11-HC (4×50mm, 47 °C, Dionex). Sodium hydroxide served as the eluent using a gradient program: 0-10 min from 2 to 5mM; 10-40 min from 5 to 40 mM. Eluent flow rate was set at 1mL/min and loop volume was 200µL.

Appendix B Theoretical feed regime for digester operation

Table B- 1 Theoretical feed regime

COD loading (%)	Volume of feed sludge to the test digester (mL)	Volume of restaurant grease to the test digester (mL)	Total Volume (mL)	Test digester HRT (day)
100	1000	0	1000	20
120	1000	6	1006	19.9
125	1000	7	1007	19.9
130	1000	9	1009	19.8
140	1000	12	1012	19.8
150	1000	15	1015	19.7
160	1000	17	1017	19.7
170	1000	20	1020	19.6
180	1000	23	1023	19.5
190	1000	26	1026	19.5
210	1000	32	1032	19.4
230	1000	38	1038	19.3
250	1000	44	1044	19.2
270	1000	49	1049	19.1
300	1000	58	1058	18.9
350	1000	73	1073	18.6
387	1000	83	1083	18.5

Appendix C Raw data of codigestion performance

Table C- 1 Raw data of daily biogas production, pH, PA and TA in the stage of baseline setup

Date	Daily biogas production (L/d)		pH		PA ($mgCaCO_3/L$)		TA ($mgCaCO_3/L$)	
	C[a]	T[b]	C	T	C	T	C	T
2010-04-04	22.528	22.247	7.28	7.29	2805	2657	4182	4163
2010-04-05	21.301	22.140	7.31	7.30	2644	2780	4140	4154
2010-04-06	23.902	25.460	7.29	7.32	2889	2884	4204	4196
2010-04-07	23.922	21.802	7.33	7.31	2751	2708	4253	4226
2010-04-08	22.777	22.926	7.32	7.35	2611	2598	4261	4090

[a] Control digester

[b] Test digester

Table C- 2 Raw data of COD, TS and VS in the stage of baseline setup

Date	COD (g/L)			TS (g/L)			VS (g/L)		
	Feed[a]	C[b]	T[c]	Feed	C	T	Feed	C	T
2010-04-04	--	26.6	27.5	--	27.8	27.8	--	15.6	15.5
2010-04-05	70.1	27.3	25.7	57.5	28.7	28.4	41.4	16.1	16.0
2010-04-06	--	27.1	25.7	--	28.6	27.6	--	15.9	15.3
2010-04-07	--	25.0	26.5	--	26.1	27.0	--	14.3	14.7
2010-04-08	67.0	26.7	26.4	52.9	28.0	27.3	37.6	15.5	15.0
2010-04-09	--	27.0	25.1	--	28.8	27.5	--	15.7	15.0
2010-04-10	--	26.7	26.6	--	29.1	28.8	--	15.8	15.7
2010-04-11	72.7	--	--	55.1	--	--	39.4	--	--

[a] Feed sludgeControl digester

[b] Effluent sludge from control digester

[c] Effluent sludge from test digester

Table C- 3 Raw data of pH for control and test digesters during different COD loading periods

COD loading period	Control digester		Test digester	
	pH	STDEV[a]	pH	STDEV
120%	7.33	0.02	7.35	0.02
125%	7.37	0.01	7.37	0.03
130%	7.29	0.03	7.29	0.04
140%	7.29	0.02	7.30	0.02
150%	7.28	0.01	7.27	0.02
160%	7.31	0.03	7.30	0.03
170%	7.31	0.01	7.28	0.01
180%	7.29	0.02	7.27	0.02
190%	7.26	0.01	7.24	0.02
210%	7.32	0.02	7.29	0.02
230%	7.28	0.01	7.23	0.02
250%	7.24	0.02	7.21	0.01
350%	7.30	0.03	7.16	0.02
387%	7.31	0.02	7.09	0.02

[a] STDEV stands for standard deviation

Table C- 4 Raw data of PA and TA for control and test digesters during different COD loading periods

COD loading period	Control digester				Test digester			
	PA (mg/L)	PA-STDEV[a]	TA (mg/L)	TA-STDEV	PA (mg/L)	PA-STDEV	TA (mg/L)	TA-STDEV
120%	3043	16	4686	44	3036	52	4642	26
125%	3027	27	4733	25	3040	40	4631	23
130%	2490	47	4089	104	2375	116	3923	93
140%	2206	n/a[b]	3604	n/a[b]	2045	5	3407	23
150%	2206	n/a[b]	3658	n/a[b]	2054	58	3440	9
160%	2206	53	3656	19	2065	32	3317	41
170%	--	--	--	--	2047	34	3336	15
190%	--	--	--	--	2013	14	3253	11
210%	2232	20	3816	37	1901	60	3221	10
230%	--	--	--	--	1882	3	3177	6
270%	--	--	--	--	1864	6	3172	8
350%	--	--	--	--	1720	51	2982	62
387%	2224	67	4010	19	1496	12	2788	26

[a] STDEV= standard deviation

[b] Only once measurement was conducted during that COD loading period, because that period lasted less than 10 days.

Table C- 5 Raw data of CO_2 content for control and test digesters during different COD loading periods

COD loading period	Control digester		Test digester	
	CO_2 content	STDEV[a]	CO_2 content	STDEV
130%	32.0%	2.7%	33.5%	1.1%
140%	--	--	30.4%	--
150%	31.9%	--[b]	31.1%	--
160%	30.4%	1.2%	28.7%	0.8%
170%	--	--	27.1%	--
180%	--	--	29.3%	--
210%	31.0%	--	29.2%	--
230%	--	--	27.5%	--
250%	--	--	27.5%	--
270%	32.0%	--	28.8%	--
350%	--	--	26.9%	--
387%	30.7%	0.6%	26.9%	0.5%

[a] STDEV= standard deviation

[b] Measurement in the loadings, other than 130%,160% and 400%, was conducted once and no standard deviation was obtained.

Table C- 6 Raw data of daily biogas production for control and test digesters during different COD loading periods

COD loading period	Control digester		Test digester		Comparison
	Biogas (L/d)	STDEV[a]	Biogas (L/d)	STDEV	Increase %
120	27.859	1.763	31.723	2.409	14
125	26.363	1.945	34.074	2.833	29
130	14.369	0.518	20.110	0.640	40
140	11.370	0.402	16.625	0.316	46
150	10.883	0.420	17.796	0.255	64
160	12.464	0.129	24.620	0.715	98
170	12.536	0.256	25.370	1.099	102
180	12.653	0.579	27.581	1.805	118
190	13.673	1.045	31.673	1.413	132
210	13.450	0.232	36.556	2.769	172
230	13.334	0.585	40.447	0.801	203
250	13.770	1.324	44.488	2.015	223
270	13.637	0.107	47.253	3.621	247
300	13.750	0.124	53.281	1.180	287
350	13.794	0.914	64.809	6.141	370
387	14.055	0.516	79.710	4.651	467

[a] STDEV= standard deviation

Appendix D Raw data and results for analysis of variance (ANOVA)

Table D-1 pH raw data at COD loading of 160% and 170%

COD loading periods	Date	pH	
		Control	Test
160%	29/08/2010	7.33	7.32
160%	30/08/2010	7.34	7.32
160%	31/08/2010	7.3	7.31
160%	01/09/2010	7.34	7.34
160%	02/09/2010	7.31	7.31
160%	03/09/2010	7.27	7.25
160%	04/09/2010	7.27	7.27
160%	05/09/2010	7.32	7.29
160%	06/09/2010	7.31	7.30
160%	07/09/2010	7.32	7.30
170%	09/09/2010	7.31	7.29
170%	10/09/2010	7.30	7.27
170%	11/09/2010	7.32	7.28

Table D-2 ANOVA results for pH at COD loading of 160%

Groups	Count	Sum	Average	Variance
Control	10	73.11	7.311	0.000632
Test	10	73.01	7.301	0.000677

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0005	1	0.0005	0.764007	0.39359	4.413873
Within Groups	0.01178	18	0.000654			
Total	0.01228	19				

Table D-3 ANOVA results for pH at COD loading of 170%

Groups	Count	Sum	Average	Variance
Control	3	21.93	7.31	0.0001
Test	3	21.84	7.28	0.0001

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00135	1	0.00135	13.5	0.021312	7.708647
Within Groups	0.0004	4	0.0001			
Total	0.00175	5				

Table D-4 PA and TA raw data at COD loading of 130%

COD loading period	Date	PA (mg/L)		TA (mg/L)	
		Control	Test	Control	Test
130%	04/07/2010	--	2457	--	4084
130%	05/07/2010	2562	2438	4225	4025
130%	06/07/2010	--	2544	--	3976
130%	07/07/2010	2511	2499	4146	3967
130%	08/07/2010	--	2341	--	3949
130%	09/07/2010	2450	2347	4104	3910
130%	10/07/2010	--	2180	--	3819
130%	11/07/2010	--	2232	--	3849
130%	12/07/2010	2475	2308	3986	3833
130%	13/07/2010	2453	2401	3986	3815

Table D-5 ANOVA results for PA at COD loading of 130%

Groups	Count	Sum	Average	Variance
Control	5	12451	2490.2	2204.7
Test	10	23747	2374.7	13356.46

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	44468	1	44468	4.480	0.054	4.667
Within Groups	129027	13	9925			
Total	173494	14				

Table D-6 ANOVA results for TA at COD loading of 130%

Groups	Count	Sum	Average	Variance
Control	5	20447	4089.4	10796.8
Test	10	39227	3922.7	8663.344

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	92630	1	92630	9.939	0.008	4.667
Within Groups	121157	13	9320			
Total	213787	14				

Table D-7 CH_4 content raw data at COD loading of 130%, 160% and 387%

COD loading periods	CH_4 content (%)	
	Control	Test
130%	--	66.7%
130%	66.4%	66.9%
130%	64.6%	65.4%
160%	62.6%	61.5%
160%	59.5%	63.3%
160%	59.8%	63.0%
160%	60.1%	62.5%
160%	59.7%	64.0%
160%	--	62.3%
160%	--	62.4%
160%	--	62.1%
387%	58.3%	64.5%
387%	60.5%	65.9%
387%	59.5%	66.4%
387%	59.6%	66.6%
387%	--	65.8%

Table D-8 ANOVA results for CH_4 content at loading of 130%

Groups	Count	Sum	Average	Variance
Control	2	1.306902	0.653451	0.000109
Test	3	1.990868	0.663623	6.62E-05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000124	1	0.000124	1.543932	0.302307	10.12796
Within Groups	0.000241	3	8.04E-05			
Total	0.000365	4				

Table D-9 ANOVA results for CH_4 content at loading of 160%

Groups	Count	Sum	Average	Variance
Control	5	3.016624	0.603325	0.000169
Test	8	5.011066	0.626383	6E-05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001635975	1	0.001636	16.445	0.001898	4.844
Within Groups	0.001094281	11	9.95E-05			
Total	0.002730256	12				

Table D-10 ANOVA results for CH_4 content at loading of 387%

Groups	Count	Sum	Average	Variance
Control	4	2.378671	0.594668	7.86E-05
Test	5	3.292093	0.658419	6.5E-05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.009031	1	0.009031	127.473	9.56E-06	5.591
Within Groups	0.000496	7	7.08E-05			
Total	0.009527	8				