FEASIBILITY STUDY OF FOOD WASTE TO ENERGY
CONVERSION THROUGH ANAEROBIC DIGESTION

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in
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by
Debasis Das
Spring 2012
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<td>American Public Health Association</td>
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<td>BMU</td>
<td>Bell Memorial Union</td>
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<td>BMW</td>
<td>Bio Medical Waste</td>
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<td>BVS</td>
<td>Biodegradable Volatile Solids</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
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<td>COD</td>
<td>Chemical Oxygen Demand</td>
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<td>OLR</td>
<td>Organic Loading Rate</td>
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<td>RVS</td>
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SRT: Solid Retention Time
TS: Total Solids
VFA: Volatile Fatty Acids
VS: Volatile Solids
FEASIBILITY STUDY OF FOOD WASTE TO ENERGY
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The current work focuses on the feasibility of generating bio-energy from food waste produced by California State University, Chico (Chico State), using anaerobic digestion process. Attempts have been made to optimize various parameters in order to determine the most favorable recipe for maximum biogas production from the digested food waste. The biogas yields have been determined using batch anaerobic thermophilic digestion tests at 50±2°C for a period of 27 days. The average Total Solid (TS), Volatile Solid (VS), and Fixed Solids (FS) of the food waste were determined to be 4.16 g/L, 3.19 g/L, and 0.5 g/L respectively. The Standard Error of Mean of the mean for TS, VS, and FS was determined to be 6.3, 5.2, and 1.5 respectively while the confidence intervals (+95%) were 6.35, 5.74, and 0.71 respectively. The total carbon content of the food waste was between 19-20%. Methane production increased in the
first week of incubation (up to day 8) in presence of 5 g, 10 g, 15 g, and 20 g of food
scraps. By day 8, 726 mg/L, 752 mg/L, 848 mg/L, and 935 mg/L of methane had been
generated from 5 g, 10 g, 15 g, and 20 g food scrap, respectively. The average methane
production over the 27 days of incubation from 5 g, 10 g, 15 g, and 20 g food scrap was
682 mg/L, 688 mg/L, 686 mg/L, and 697 mg/L, respectively. The Standard Error of
Mean for methane production from 5 g, 10 g, 15 g, and 20 g food waste was determined
to be 24.1, 17.6, 19.6, and 22.7 respectively while the confidence intervals (+95%) were
729.1, 722.2, 724.6, and 741.2 respectively. However, a characteristic oscillation was
observed in the rate of methane production, with decline in production in day 10
followed by an increase in the subsequent days of incubation. This may be due to the
presence of methylotroph population in the activated sludge, which uses methane as a
carbon source for their growth. The total biogas generated in the system over the
experimental period was the sum of methane and carbon dioxide. The concentrations of
both gases were determined through a Gas Chromatograph. Biogas produced from the
decomposition of food waste was a mixture of 76% methane and 24% carbon dioxide.
CHAPTER I

INTRODUCTION

In this rapidly growing world, energy has become synonymous with economic development. Hence as economies grow so is the demand for energy, putting acute pressure on the more conventional form of energy that we use today namely fossil fuels. And because fossil fuels are a non-renewable source of energy with limited resources, it becomes difficult to meet our entire energy requirement through them. Another downside to the use of fossil fuels is its adverse impact on the environment. Thus, the current need is for a cleaner, greener, renewable, and economically feasible source of energy [Han and Shin, 2004; Holm-Nielsen et al., 2009]. The objective of the current study is to evaluate methane production from food waste for its further use as a biofuel that would have eventually landed up in landfills generating toxic gases. The focus of this work is both waste utilization and energy production.

Food wastes are generally biodegraded in the process of anaerobic digestion to produce biogases. Anaerobic digestion (AD) is a biological process in which biodegradable organic matter is broken down by microorganisms in the absence of oxygen into biogas which consists of methane (CH₄), carbon dioxide (CO₂), and trace amounts of other gases [Yang et al., 2004]. AD is advantageous because it is a renewable source of energy and reduces the emission of landfill gases. The nutrient rich solids left after digestion can also be used as an organic soil amendment [Cho et al., 1995].
It has been reported that anaerobic digestion has been used as a major technique for management of waste produced from municipal as well as industrial sources since many years [Agdag and Sponza, 2007; Salminen and Rintala, 2002] Only in the past decade has the technology become a recognized method for processing solid organic waste from residential and commercial sources. The benefit of an AD process is that it is a net generator of energy which can be sold in the form of heat, steam or electricity.

Wastewater from multiple sources like, municipal, food processing industries, leather industries, and animal husbandry are exposed to treatment through the anaerobic digestion technique. Many European countries like Denmark, France, and Germany are now leaders in organic waste-management, using the AD technique [Holm-Nielsen et al., 2009]. The biogas produced usually consists of around 60% methane (CH$_4$), followed by carbon dioxide and trace amount of ammonia [Rasi et al., 2007]. Methane can be used to fuel a Combined Heat and Power (CHP) system for electricity and heat generation, refined for addition to existing gas supply networks, used as a vehicle gas, or used in conventional gas boilers or engines for separate heat or electricity generation. Methane has approximately 21 times the greenhouse gas effect of CO$_2$ [Wuebbles and Hayhoe, 2002]. Decomposition of food waste in open space results in release of methane gas to the atmosphere. Therefore, implementation of AD process not only displaces conventional generation it also helps to reduce natural greenhouse gas emissions. The nutrient rich product of the AD process can be applied in soils to improve soil fertility. The same can also be used as compost in horticulture and other agricultural practices. In case of Chico State this can be used at the University Farms. Thus, the best use of AD is to combine both waste management and its by-products use [Kim et al., 2004].
Objectives

The objectives of this research fall into two broad categories. The first looked into determining the technical feasibility of using anaerobic digestion to reduce Chico State’s food waste and the second objective was to determine the optimum recipe to generate the maximum amount of biogas.

The thesis is based on separate studies covering four different aspects.

1. To characterize the physical properties of the food waste that is collected from Bell Memorial Union (BMU), Chico State.

2. To determine the potential of this food waste as a feedstock for a thermophilic anaerobic digester.

3. To determine the overall variability and consistency of Chico State food waste over time.

4. To study the feasibility of converting the food waste into biogas energy for Chico State.
CHAPTER II

REVIEW OF LITERATURE

Food Waste

Food waste is “any food substance, raw or cooked, which is discarded, or intended or required to be discarded,” according to the legal definition of waste by the European Union Commission (EUC) (http://archive.defra.gov.uk/environment/waste/topics/documents/ECJCaseLaw20090209.pdf). Food waste is further divided into many categories depending on the norm through which it is processed, used, and then discarded. According to the survey of United States Environmental Protection Agency (USEPA), components of food waste happen to be one of the largest part of the overall Municipal Sewage waste generated in the entire USA [Heller and Keoleian, 2003]. The load of food waste generally includes uneaten and left over food from residential as well as commercial areas like hotels, restaurants, cafeteria, school/university campus and other commercial establishments. It has been reported by California Integrated Waste Management Board [Carr, 2004] that 5.6 million tons (wet) and 2.2 million tons (dry), per year, is generated in California state. Another statistical study indicated the pre-consumer food waste generated by Chico State was 50.38 tons for 2007, 58 tons for 2008, 51.93 tons for 2009 and 46.31 tons for 2010 (Eli Goodsell, Recycling Operations Coordinator, CSU, Chico, Associated Students Recycling, unpublished data, 2011). The food waste is usually disposed of in landfills. The major challenge of the current era has
been to maintain a balance between economic growth and sustainable practices which would result in a cleaner and greener environment for our future generations. Therefore, many researchers around the world are focused to utilize the food waste a potential source of cost effective and sustainable energy source [Schneider, 2008]. The disposal of organic food wastes into landfills is being forbidden in many countries in order to reduce the generation of green house gases [Rao and Singh, 2004; Holm-Nielsen et al., 2009]. In this context, the research focus is shifting towards development of eco-friendly techniques to abate the food waste generated from various sources [Holm-Nielsen et al., 2009]. Attempts are also being made to further utilize the organic waste towards production of alternative fuel as biomass offers worldwide the major exploitation potential among renewable energy sources [Han and Shin, 2004].

In underdeveloped and developing countries the amount of food waste generated is very low and may not be suitable for successful operation of AD process whereas in developed nations huge amount of food waste is generated. The later can be viable as a potential source for generation of alternative energy primarily through AD process [Levis et al., 2010].

**Anaerobic Digestion**

Anaerobic digestion (AD) is a biological process in which biodegradable organic matter is broken down by microorganisms in the absence of oxygen into biogas which consists of methane (CH₄), carbon dioxide (CO₂), and trace amounts of other gases. AD typically converts the organic waste into biogas at an increasing rate for the first two weeks after which the rate of conversion is constant until the organic source is
consumed [Lastella et al., 2002]. On-site treatment of sewage in combination with vegetable, fruit and yard waste have at low temperature conditions have been proposed [Zeeman and Letinga, 1999] and the authors throw light on determination of Hydraulic Retention Time (HRT) when a certain Solid Retention Time (SRT) is prerequisite in various reactor systems like Upflow Anaerobic Sludge Blanket (USAB), Continuous Stirred Tank Reactor (CSTR) and Accumulation Systems (AC). AD is widely used to treat wastewater sludge and organic waste. AD is advantageous because it is considered to be a sustainable process with low cost, less space consuming operational units, it is a renewable source of energy, reduces the emission of landfill gases, and the nutrient rich solids left after digestion can be used as an organic soil amendment. The reuse of anaerobically digested sludge in agriculture from an environmental point of view has also been investigated [Chen et al., 2008; Hospido et al., 2010] by using Life Cycle Assessment (LCA) methodology. The authors have quantified the environmental impact associated with the application of digested sludge on agricultural soil in terms of eutrophication, global warming potential due to production of greenhouse gases like methane and nitrous oxide, as well as human and terrestrial toxicity due to the emerging micro pollutants like personal and pharmaceutical products (dissolved/sorbed) associated with the sludge.

**Conditions and Variables Influencing AD**

There are several conditions and variables that must be adjusted in order to obtain a proper breakdown of the organic compounds. The operating parameters of the anaerobic digester must be controlled to enhance the microbial activity and thus increase the AD efficiency. Some of these parameters are discussed briefly in the following
section. The potential of anaerobic digestion for material recovery and energy production has also been studied [Salminen and Rintala, 2002]. The study was basically a review providing substantial information regarding the applicability of AD for energy production. The potential of AD for energy production from fruit, vegetable, and yard wastes has been investigated giving an overview of the various operational techniques along with the significant parameters for optimum energy production through AD [Bouallagui et al., 2005]. Food waste collected in San Francisco, California was characterized to assess its prospective as a feedstock in AD process. The study indicated that food waste, in relation to its biodegradable characteristics with simultaneous yield of biogas, hold great potential to be used as a suitable substrate for AD process [Zhang et al., 2007].

Extensive research has also been conducted on anaerobic digestion of animal manure. In California over 15 dairy manure digester plants are operational (San Joaquin Valley Dairy Manure Technology Feasibility Assessment Panel, http://www.arb.ca.gov/ag/caf/dairypnl/dmtfapprprt.pdf). To increase the economic viability of the technology rigorous R&D efforts have been initiated to enhance the biodegradability of the dairy manure for better yield of biogas. Anaerobic digestion of dairy manure in batch scale and mesophilic (35°C) conditions has been studied and a first order kinetic model has been developed to determine the methane yield from various mixtures of food wastes and unscreened dairy manure. With addition of food waste into the manure digester, an increased yield in methane production over a period of 20 days has been noticed [El-Mashad and Zhang, 2010]. The study also indicated a methane yield (301, 228, and 241 L/KgVS) after 30 days of using fine as well as coarse fractions of screened and
unscreened manures. Following 20 days of anaerobic digestion process 93%, 87%, and 90% biogas production was achieved with an average methane content of 69%, 57%, and 66% respectively. It has also been reported that after 30 days of digestion of two unscreened manure mixtures (68/32% and 52/48%), 282 and 311 L/KgVSS of methane gas were generated and approximately 90% and 95% of biogas yield was obtained respectively after 20 days. Therefore, 20 days of Hydraulic Retention Time (HRT) can be ideally recommended for a continuous anaerobic digester. The model has been shown to predict a significant increase in methane yield during 20 days of digestion by further addition of food waste into the manure digester (up to 60% of the initial volatile solid).

**Total Solid Content**

Total Solid (TS) of a medium is considered to be the overall dissolved and particulate solid present in the wastewater medium. Therefore, according to the size fraction of the solid particles the TS is usually differentiated into Total Dissolved Solids (TDS) and Total Suspended Solids (TSS). This is actually an operational difference, whereby all the solid particles passing through a filter paper of 1.5 microns are considered as dissolved solid particles where as those detained in the filter paper are considered to be suspended solid particles. AD process can be diversified according to three different ranges of solid content: low solid (LS) AD systems contain less than 10% Total Solid (TS), Medium Solid (MS) from 15-20% and High Solid systems (HS) range from 22-40% [Tchobanoglous et al., 1993]. Some feedstock may need water added to it in a co-digestion plant. This can be achieved by mixing high TS material with wetter waste types [Ponsa et al., 2008].
Temperature

Anaerobic digestion can occur under two main temperature ranges:

- **Mesophilic conditions**, between 25 - 40°C, usually 35°C.
- **Thermophilic conditions**, between 45 - 122°C.

Usually the optimum temperature in an AD process shows variation depending on the digester type as well as the composition of the food waste. However, the temperature of the reactor (carrying out the AD) is a crucial parameter that needs to be monitored and maintained to achieve a higher rate of gas production. The sterilization of the waste is also linked to the temperature. Higher temperature is most effective at eliminating pathogens, and viruses (e.g., *E.coli*, *Salmonella*, etc.).

The influence of temperature and Hydraulic Retention Time (HRT) on the performance of AD of cow manure in completely stirred tank reactors has been studied. The results revealed higher methane production at a temperature of 50°C and 20 days HRT. The potential use of solar energy to heat the reactor system has also been taken into consideration [El-Mashad et al., 2004].

The study of AD of food wastes in a modified three-stage methane fermentation system revealed that biogas generation was higher at thermophilic temperature conditions rather than the mesophilic conditions, irrespective of the HRT [Kim et al., 2006].

Retention Time

Retention time is the time needed to achieve the complete degradation of the organic matter. The retention time varies with process parameters, such as process
temperature and waste composition. The retention time for waste treated in a mesophilic digester ranges from 15-30 days and 12-14 days for thermophilic digester.

Parameters such as Organic Loading Rate (OLR), HRT and temperature are considered to be crucial towards determining process control mechanisms that might lead to instability in anaerobic digestion. It was observed that the accumulation of volatile fatty acids in the reactor system had a negative impact on AD thus decreasing the biogas production [Mechichi and Sayadi, 2005].

Mixing

In order to enhance the contact between the microorganisms and the organic substrate, proper mixing of the entire constituent is a crucial factor. Proper mixing helps in maintaining a homogenous state and also enhances the rate of digestion by preventing temperature stratification and crust formation inside the reactor. However, excessive mixing of the components needs to be avoided as it would disturb the stability of the reactor [Kaparaju et al., 2008]. Digestion of more than one substrate in the same digester is termed as co-digestion. This process of co-digestion supports the growth of microorganisms in the presence of additional nutrients provided by the respective substrates and thus facilitates higher methane yield in the medium. Proportionate mixing of various feedstock is essential to maintain a homogeneity while adapting co-digestion technique. This helps in creating a suitable environment for the microorganisms to carry out their metabolic activities in the reaction medium [El-Mashad and Zhang, 2010].

The effect and mode of mixing (biogas and slurry recirculation and impeller mixing) and waste strength on the performance of laboratory scale digesters have been investigated [Karim et al., 2005]. The study indicated that at constant HRT, mixing did
not have much impact on production when the reactor was fed with 5% manure slurry. However, the effect and mode of mixing were more prominent with thicker manure slurry (10%). It was concluded that mixing issue becomes a critical parameter with thicker slurries.

**Volatile Solids**

Volatile Solids (VS) represent the combustible organic matter in a sample that are lost on ignition of the dry solids at around 550°C. VS comprise a biodegradable VS (BVS) fraction and refractory VS (RVS) fraction. Knowledge of BVS fraction is very important with relation to the AD process as the former gives an estimation of OLR, biodegradability of the waste, carbon/nitrogen ratio and biogas generation. RVS comprise of a complex organic matter called lignin, which is not easily degraded by the anaerobic microorganisms. It has been reported that a high BVS content with low RVS is more suitable for AD [Kayhanian, 1995].

Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system. It has been observed that OLR plays a significant role in biogas generation through the AD process particularly in continuous reactor systems. A high OLR usually results in the accumulation of several inhibitory substances such as fatty acids which has a negative impact on the overall process [Ince et al., 1995]. The increase in OLR on the performance of a reactor performing anaerobic thermophilic digestion has been investigated. It was observed that thermophilic sludge digester could achieve significant VS and COD (Chemical Oxygen Demand is the total measurement of all the chemicals in water that can be oxidized by a strong chemical oxidizing agent) removal
Biochemical Processes

There are three main stages in the biochemical process of AD: hydrolysis, acidogenesis, and methanogenesis, which are shown in Figure 1 [Metcalf and Eddy, 1985].

Fig. 1. Biological process of anaerobic digestion.

Hydrolysis

Certain hydrolytic microorganisms secrete extracellular enzymes that play a crucial role in hydrolysis of the substrate. This is considered to be the very first step in the AD process in which the complex substrate molecules like fat, protein and carbohydrates are converted/hydrolyses to their respective simpler forms like fatty acid,
amino acid and simple sugar. These simpler molecules are then exposed to the process of acitogenesis [Metcalf and Eddy, 1985]:

<table>
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<th>Lipid</th>
<th>→</th>
<th>Fatty Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysaccharide</td>
<td>→</td>
<td>Monosaccharide</td>
</tr>
<tr>
<td>Proteins</td>
<td>→</td>
<td>Amino acids</td>
</tr>
</tbody>
</table>

**Acetogenesis**

It is a biological reaction where simple monomers are converted into volatile fatty acids (VFA). This is the second stage of the anaerobic digestion process in which H₂ gas is also generated as a byproduct along with VFA and alcohol [Wang et al., 2005]. This stage is also known as the acidogenic or fermentative stage in an anaerobic digestion process. The activity of microorganisms during the start-up of acidogenic anaerobic reactors at mesophillic and thermophillic temperature ranges has been studied [Liu et al., 2002]. It has been reported that in thermophillic reactors the microbial consortia changed more rapidly than in mesophillic reactor systems performing AD process. Hence, it has been suggested that acclimatization of the microbial consortium is an important parameter to maintain the stability of the reactor performing AD. Under optimum conditions of temperature (30°C) and mixing ratio the acidogenic microorganisms generate volatile fatty acids, carbon dioxide, ammonia, and hydrogen from the hydrolyzed products mentioned above [Metcalf and Eddy, 1985].

**Methanogenesis**

The third stage produces CH₄ by methanogenic bacteria that utilize/decompose the products of the acetogenic stage. A certain group of acidophilic microorganisms called acidotrophic bacteria generate around 70% of CH₄ from volatile
fatty acids while the rest 30% is generated by hydrogenotrophic microorganisms from carbon dioxide and hydrogen [Sowers, 2010]. A rise in hydrogen level disturbs the reaction stability in an AD process resulting in a decline in the activity of the acedogenic microorganisms. Thus, there is a fall in the biogas production rate. Therefore, the role of hydrogenotrophic microorganisms is crucial in maintaining a low level of hydrogen in the reactor. Methanogenic microorganisms are very sensitive to change in reaction parameters hence it is essential to maintain the reactor in steady state for stable CH₄ production.

\[
\begin{align*}
\text{CH}_3\text{COOH (acetate)} & \rightarrow \text{CH}_4 + \text{CO}_2 \\
2\text{C}_2\text{H}_5\text{OH (ethanol)} + \text{CO}_2 & \rightarrow \text{CH}_4 + 2\text{CH}_3\text{COOH} \\
\text{CO}_2 + 4\text{H}_2 (\text{hydrogen}) & \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
\end{align*}
\]

Biogas, specifically CH₄, is a renewable energy source which has become the need of the day. However CO₂ and CH₄ being greenhouse gases are a cause of concern for the entire mankind. CH₄ can be collected through anaerobic digestion of various wastes, stored and used as a source of energy. The purpose of using CH₄ is to generate energy and to reduce the greenhouse gases from the atmosphere [Rao and Singh, 2004].

Further assessment of using food waste as a desirable feedstock for AD processes has shown some interesting findings. A methane yield of more than 400 mL/g VS following 20 days of digestion of food waste at 50°C, makes the same a very suitable feedstock for AD process. It has also been reported that approximately 80% of methane yield was attained during the initial 10 days of the AD process [Zhang et al., 2007].
General Process Description

There are two possible aims of using AD. It can be used either to treat biodegradable wastes or produce saleable products (heat/electricity, soil amendment). Energy crops can be grown and then used for AD. In this case, the aim is to produce as much biogas as possible. A good quality soil amendment is another byproduct. Especially for waste management, it is unlikely that AD will be a viable treatment without using the biogas and the digestate as both of these are potential pollutants. The biogas is a greenhouse gas and the digestate might contain pathogenic microorganisms and other undesirable byproducts; however, their qualities will vary depending on the feedstock and its contamination. The process of AD can be further divided into four stages; pre-treatment, digestion, gas upgrading, and composting digestate. The level of pre-treatment depends on the type of feedstock (e.g., manures need to be mixed, whereas municipal solid wastes (MSW) are sorted and shredded).

The digestion stage takes place in the digester [Wang et al., 2005]. There are many types of digesters with different temperature, mixing devices, etc. The digestion can be either dry or wet depending on the solid content. Thus, the feedstock can be mixed with water and other appropriate liquid wastes such as sewage or re-circulated liquid from the digester effluent.

The biogas produced during the digestion stage has to be upgraded because it contains impurities that can damage boilers or engines. Hydrogen sulfide and water vapor need to be removed for boilers and combined heat and power units. Removal of carbon dioxide will be required if the gas is to be used as natural gas or vehicle fuel.
Figure 2 shows the general process of a co-digestion plant which means that two different types of waste are mixed as described earlier.

Fig. 2. General process for an AD co-digestion plant.
CHAPTER III

METHODOLOGY

Food Waste Collection and Physico-chemical Analysis

Pre-consumer food waste sample was collected from the trashcans of Bell Memorial Union (BMU), in zip lock bags and immediately transferred to the cold room in the Chemistry Department of Chico State. The sample was predominantly tomato, cucumber peels, carrot peels bell pepper, onions, cilantro, cooked rice, and breadcrumbs.

The compositional variability of all collected food waste samples are analyzed for Moisture Content (MC), Total Solids (TS), Volatile Solids (VS), and Fixed Solids (FS) according to the standard methods (for the examination of water and wastewater, which is Published by American Public Health Association (APHA) [APHA, 1989]. The food waste sample was also analyzed, in triplicate, for carbon using the Total Carbon Analyzer (Shimadzu, Kyoto, Japan) [Yang et al., 2004].

Procedure for MC, TS, VS, and FS

The food waste sample was finely ground to maintain homogeneity. Specific amounts of food sample were weighed, using an OHAUS Adventurer Pro AV313 in three separately prepared evaporating dishes. The evaporating dishes were also weighed individually using the same balance and were then placed in an oven at 105°C overnight and weighed again the next morning. The evaporating dishes were then transferred to a
cool muffle furnace heated to 550ºC ± 50ºC and ignited for an hour to remove volatile organics.

**Calculation**

The percentage of Total Solids was calculated using Equation 1:

\[
\% \text{ Total Solids} = \frac{(A - B) \times 100}{C - B}
\]  

(1)

Similarly, the percentage of Volatile Solids was calculated using Equation 2:

\[
\% \text{ Volatile Solids} = \frac{(A - D) \times 100}{A - B}
\]  

(2)

And the percentage of fixed solids was calculated using Equation 3:

\[
\% \text{ Fixed Solids} = \frac{(D - B) \times 100}{A - B}
\]  

(3)

Where:

- \(A\) = weight of dried residue + dish, mg
- \(B\) = weight of dish, mg
- \(C\) = weight of wet sample + dish, mg
- \(D\) = weight of residue + dish after ignition, mg

**Anaerobic Digestion Tests**

Batch digestion tests were performed on food waste to determine its biodegradability (ASTM D5511 - 02). The batch digestion tests were performed as described in Anaerobic Lab Work [1992]. The food waste for digestion was prepared by mixing all food wastes and taking representative samples from the mixture. These
representative samples were then digested in 15 batch digesters (500 mL each) at four initial loadings (5 g, 10 g, 15 g, and 20 g food waste), each in triplicate, and a thermophilic temperature of 50ºC±2ºC. At the beginning of the digestion tests 100 mL of bacterial inocula (sludge from the Municipal Wastewater Treatment Plant in Chico) were mixed with a predetermined amount of food waste sample and 200 mL of tap water, bringing the effective volumes of each digester to 300 mL. After the inoculum, water, and food waste sample were added to the digester, the headspace of each digester was purged with nitrogen gas for about 30 seconds to ensure anaerobic conditions. After this, each digester was tightly closed with a rubber septa and a metal wire was tied around the outside mouth of the digester. Three blank digesters that contained inoculum and water only (no food waste sample) were also incubated at the same temperature (Figure 3).

![Fig. 3. Digesters inside the incubator during Anaerobic batch digestion.](image-url)
Biogas Measurements

The methane production from each digester was measured every other day. 500 µL of biogas were drawn using a syringe (1000 µL or 1 mL made by Hamilton Company, Reno, Nevada). This was then injected into a gas chromatograph (SRI Model 310) to analyze the biogas for CH₄ and CO₂ (ASTM E 260). The gas chromatograph was equipped with a thermal conductivity detector and helium gas was used as a carrier. Molecular Sieve column (Alltech HAYESEP DIP 100/120 9’X1/8”X0.085” SS) was used in the gas chromatograph and column head pressure was retained at 350 kPa while the thermal conductivity and temperature of the oven were 130 and 110°C respectively. A standard gas (60% v/v CH₄ and 40% CO₂) was used during calibration of the instrument. Instrument calibration was performed on a regular basis throughout the experimental period:

**Step-1:** Initially pressure measurements were taken.

**Step-2:** Followed by drawing the biogas from the digester (for the measurement of concentration of methane and carbon dioxide through the GC).

**Step-3:** Total biogas in the headspace was vented under water to prevent gas exchange between the headspace and the ambient air (Figure 4).

Then the pressure in the headspace was used as the initial condition for the next measurement (ASTM E 355).
Fig. 4. Venting of the biogas from the headspace of the digester.

Data Analysis

Chromatographic peak areas of methane and carbon dioxide in biogas were obtained using Logger Pro version 3.6.1 software. The peak area is related to the amount of each gas. The formulae used to determine methane was:

\[ A (\text{CH}_4) = K (\text{CH}_4) \times Q (\text{CH}_4) \]  \hspace{1cm} (4)

Where:

- \( A = \text{Average peak area} \)
- \( K = \text{Constant} \)
- \( Q = \text{Amount of methane injected into the GC} \)

For the gas standard, the values of both \( A \) and \( Q \) were known and the Constant \( K \) was the only unknown factor. Here the value of \( K \) was found using Equation 5:

\[ K (\text{CH}_4) = \frac{A (\text{CH}_4)}{Q (\text{CH}_4)} \]  \hspace{1cm} (5)
Where:

\[ A \text{ (CH}_4\text{)} = \text{the average of the measured peaks for CH}_4\text{ of the gas standard.} \]

\[ Q \text{ (CH}_4\text{)} = \text{the amount of CH}_4\text{ injected in the GC, in this case 300 µL.} \]

Now we have the value of the constant \( K \text{ (CH}_4\text{)} \) and the value of \( A \text{ (CH}_4\text{)}, \) which is the average areas of the peaks measured by the GC. Hence, the unknown \( Q \text{ (CH}_4\text{)} \) (i.e., the methane generated by the digesters can be determined using Equation 6).

\[ Q \text{ (CH}_4\text{)} = \frac{A \text{ (CH}_4\text{)}}{K \text{ (CH}_4\text{)}} \tag{6} \]

The same method was used to determine the amount of CO\(_2\) in the biogas generated.

**Statistical Analysis**

Linear regression between methane and carbon dioxide was done using MS Excel.
CHAPTER IV

RESULTS AND DISCUSSION

Food Waste Characteristics

Characteristics of the collected food wastes have been determined in the procedure described in the materials and methods. The concentrations of TS, VS, and FS were observed to be 4.16 g/L, 3.69 g/L, and 0.5 g/L respectively (Table 1.). The average of VS/TS (in %) shown in Figure 5, during three different months indicated that VS/TS was high thus favoring the anaerobic digestion process. The food sample tested for VS/TS in the first month (15 December 2008) was used in the AD experiment while the other two samples were discarded after testing.

<table>
<thead>
<tr>
<th>Table 1. Average of TS, VS, and FS of the Food Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (g/L)</td>
</tr>
<tr>
<td>Total Solids (TS)</td>
</tr>
<tr>
<td>Volatile Solids (VS)</td>
</tr>
<tr>
<td>Fixed Solids (FS)</td>
</tr>
</tbody>
</table>

Carbon Analysis

The carbon composition (percentage), with the standard deviations as indicated by the Y error bars, of the food waste sample used in the AD experiment is presented in Figure 6. The total carbon content of the food scraps ranged between 19% to 20%.
Fig. 5. Average VS/TS of food waste at different times.

Fig. 6. Total carbon content (%) in various food waste samples used for AD.
Due to limited access to the laboratory housing the Total Organic Carbon analyzer, dried food waste samples were stored carefully and analyzed as per the availability of the instrument.

Biogas Measurement

The biogases methane and carbon dioxide were measured using gas chromatography. The amount of methane generated from food scraps (Blank, 5 g, 10 g, 15 g, and 20 g) at different times (time interval of 48 hours during the week days and 72 hours during the weekends) has been presented in Figure 7. The blank set contained the bacterial inoculum (activated sludge) along with water without any food scrap. It was observed that during the entire 27 days of incubation, methane production in the blank set
did not follow a set pattern and varied between 498 mg/L to 675 mg/L. Methane production in the blank set may be attributed to the activity of the methanogens which are ubiquitous in the activated sludge. The methanogens (a family of microorganisms capable of producing methane gas from organic matter) usually thrive on the organic substances present in the biomass (activated sludge) converting the later to methane gas during incubation under strict anaerobic conditions in the absence of external nutrient source. This is also an indication that methanogenic bacteria can thrive in normal water and sludge (with meager nutrient). It was also observed that the methane generation in the blank set is always lower in comparison to the sets that had been supplied with food scraps (Figure 7). The only exception can be seen in day 3 where the methane generation in blank set has exceeded the set supplemented with 5 g of food scrap by ~ 5% error.

Methane production has been adjusted by subtracting the blank set data from the data obtained after the addition of various quantities of food scrap (Figure 8). Maximum methane (935 mg/L: without subtracting the blank set, and 402 mg/L after subtracting the blank set) was generated on day 8 in the presence of 20 g of food scrap. The observed fall in the rate of methane production in day 3 is attributed to the bacterial lag phase (due to the stress induced by the transfer of the biomass from the sewage treatment plant to the bottles). Subsequently the rate of production increased up to day 8 in various sets when supplied with food scraps (Figure 9). The rate declined on day 10 of the incubation followed by a rise in the subsequent days. The initial rise in the rate of production might be due to the increase in the bacterial activity until day 8 that can be correlated with the bacterial logarithmic growth phase (log-phase). Subsequent fall in the rate of production might be associated with the stationary phase of growth of the bacteria.
Fig. 8. Adjusted by subtracting the blank methane production over the days of incubation (in mg/L).

Fig. 9. Rate of methane production per day.
The oscillations (decrease in methane concentration and productions) may be due to the presence of methylotroph population in the activated sludge. These methylotrophs are a diverse group of microorganisms that use methane as carbon source for their growth and hydrogen production. The rate of methane production per day was determined using the following equation:

\[
\text{Rate of production} = \frac{dx}{dt}
\]

where \(dx\) = Increase in concentration of methane and \(dt\) = Time in which the change in concentration takes place.

The rate of methane generation (per day) shown in Figure 9 indicates that the bacterial growth shows an initial increase followed by a decline phase. Figure 10 depicts the average of the overall methane production from total food scraps used. The graph shows a similar trend as Figure 9, where there is an initial rise in the methane production followed by a decline phase, which is attributed to the overall bacterial activity in the system.

Methane production in presence of different weights of food samples as well as blank set is shown in Table 2. The cumulative production of methane in different sets during the 27 days incubation period ranged between 6000 to 8500 mg/L.

**Correlation Between Methane and Carbon Dioxide Production**

Biogas is mainly composed of methane and carbon dioxide along with trace amount of moisture and other gases like hydrogen sulfide [Holm-Nielsen et al., 2009]. In the current study biogas produced from the decomposition of food waste has been assumed to consist of 80% methane and 20% carbon dioxide, as adequate instrumentation
Fig. 10. Average of methane production over 27 days of incubation period for all the different weights of food scraps.

Table 2. Methane Production in mg/L

<table>
<thead>
<tr>
<th>Days</th>
<th>Blank</th>
<th>5 g food</th>
<th>10 g food</th>
<th>15 g food</th>
<th>20 g food</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500.75</td>
<td>609.71</td>
<td>667.74</td>
<td>666.44</td>
<td>677.50</td>
</tr>
<tr>
<td>3</td>
<td>548.66</td>
<td>484.66</td>
<td>555.29</td>
<td>550.92</td>
<td>678.90</td>
</tr>
<tr>
<td>6</td>
<td>674.51</td>
<td>843.21</td>
<td>806.60</td>
<td>690.15</td>
<td>683.63</td>
</tr>
<tr>
<td>8</td>
<td>533.37</td>
<td>726.02</td>
<td>751.68</td>
<td>848.16</td>
<td>934.51</td>
</tr>
<tr>
<td>10</td>
<td>584.51</td>
<td>713.60</td>
<td>693.93</td>
<td>662.26</td>
<td>674.40</td>
</tr>
<tr>
<td>13</td>
<td>611.12</td>
<td>695.97</td>
<td>695.15</td>
<td>694.36</td>
<td>680.13</td>
</tr>
<tr>
<td>15</td>
<td>602.07</td>
<td>706.92</td>
<td>725.01</td>
<td>696.95</td>
<td>684.05</td>
</tr>
<tr>
<td>17</td>
<td>564.29</td>
<td>672.78</td>
<td>636.23</td>
<td>673.20</td>
<td>626.19</td>
</tr>
<tr>
<td>20</td>
<td>551.79</td>
<td>638.72</td>
<td>643.93</td>
<td>628.20</td>
<td>627.63</td>
</tr>
<tr>
<td>22</td>
<td>594.27</td>
<td>712.23</td>
<td>697.04</td>
<td>704.59</td>
<td>693.70</td>
</tr>
<tr>
<td>24</td>
<td>580.70</td>
<td>692.30</td>
<td>693.73</td>
<td>701.46</td>
<td>692.32</td>
</tr>
<tr>
<td>27</td>
<td>497.43</td>
<td>686.23</td>
<td>665.38</td>
<td>717.85</td>
<td>706.92</td>
</tr>
<tr>
<td>Cumulative production</td>
<td>6843.47</td>
<td>8182.36</td>
<td>8251.72</td>
<td>8234.55</td>
<td>8359.88</td>
</tr>
</tbody>
</table>
facilities were not available to measure the trace components. It can be seen from Figure 11 that a significantly higher quantity of methane is produced in comparison to carbon dioxide when food scrap is subjected to anaerobic digestion process. Figures 12 through 16 present the correlation between methane and carbon dioxide production rate during anaerobic digestion. It can be observed that in the presence of various quantities of food scrap, methane showed a positive correlation with carbon dioxide during the anaerobic digestion. Any amount of food scrap from 5 g – 20 g leads to an increase in biogas production. This suggests that an increase in concentration of nutrient perhaps is not the only factor responsible for enhancing production of both the gases simultaneously with
Fig. 12. Linear regression of methane and carbon dioxide in presence of 5 g food scrap.

Fig. 13. Linear regression between methane and carbon dioxide production in presence of 10 g food scrap.
Fig. 14. Linear regression between methane and carbon dioxide production in presence of 15 g food scrap.

Fig. 15. Linear regression between methane and carbon dioxide production in presence of 20 g food scrap.
the progress in anaerobic digestion process. Further investigation is required to draw a
significant conclusion regarding the overall phenomenon. In the blank set, a positive
correlation is observed between the gases even though the overall biogas production rate
is lower as discussed earlier (Figure 16).

Pressure Generated Due to Biogas
Production in the Digester

It can be observed from Figure 17 that pressure generated in the digesters was
higher than that generated in the blank set. Pressure generation showed an increasing
trend until day 8 of incubation followed by a gradual decrease in the subsequent days of
incubation. This observation is in accordance with methane and carbon dioxide
production as has been described earlier. Maximum (14.39kPa) pressure generation was
Fig. 17. Pressure generated during biogas production in presence of different weights of food waste over the days of incubation observed on day 8 of incubation in presence of 20 g of food waste. The minimum (1 kPa) pressure generation was observed in the blank set on day 27 of incubation.

Using ideal gas law (PV = nRT), the number of moles of biogas generated has been determined using the pressure readings (Table 3). It can be noted that on each day of observation, the entire biogas generated was vented as has been explained in Chapter III. Therefore, in order to determine the total biogas generated during the period of study a cumulative addition was done for each set.

From Table 3, it has been determined that in presence of 5 g, 10 g, 15 g, and 20 g food waste the cumulative moles of biogas generated over 27 days of incubation is higher than blank. Though on day 8, maximum moles of biogas has been generated in presence of 20 g food scrap but the cumulative values show more or less similar values.

As per the ideal gas law methane departs at high pressures. We have assumed ideal gas law to be appropriate for the current set up since the pressures generated during
Table 3. Moles of Biogas Generated During AD (Calculated Using the Ideal Gas Law)

<table>
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<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank</td>
<td>0.0222</td>
<td>0.0228</td>
<td>0.0235</td>
<td>0.0236</td>
<td>0.0231</td>
<td>0.0226</td>
<td>0.0224</td>
<td>0.0223</td>
<td>0.0222</td>
<td>0.0220</td>
<td>0.0217</td>
<td>0.2484</td>
</tr>
<tr>
<td>5g</td>
<td>0.0231</td>
<td>0.0234</td>
<td>0.0236</td>
<td>0.0238</td>
<td>0.0231</td>
<td>0.0228</td>
<td>0.0227</td>
<td>0.0224</td>
<td>0.0223</td>
<td>0.0221</td>
<td>0.0219</td>
<td>0.2512</td>
</tr>
<tr>
<td>10g</td>
<td>0.0238</td>
<td>0.0239</td>
<td>0.0240</td>
<td>0.0240</td>
<td>0.0232</td>
<td>0.0229</td>
<td>0.0226</td>
<td>0.0224</td>
<td>0.0224</td>
<td>0.0222</td>
<td>0.0221</td>
<td>0.2535</td>
</tr>
<tr>
<td>15g</td>
<td>0.0236</td>
<td>0.0238</td>
<td>0.0243</td>
<td>0.0237</td>
<td>0.0230</td>
<td>0.0228</td>
<td>0.0226</td>
<td>0.0225</td>
<td>0.0223</td>
<td>0.0222</td>
<td>0.0221</td>
<td>0.2529</td>
</tr>
<tr>
<td>20g</td>
<td>0.0235</td>
<td>0.0245</td>
<td>0.0246</td>
<td>0.0237</td>
<td>0.0229</td>
<td>0.0228</td>
<td>0.0225</td>
<td>0.0224</td>
<td>0.0222</td>
<td>0.0221</td>
<td>0.0219</td>
<td>0.2531</td>
</tr>
</tbody>
</table>
the experiment was low (Figure 17). Methane generation during 27 days of incubation is shown in Table 4. It has been estimated that the cumulative methane generation over 27 days of incubation in presence of various 5 g, 10 g, 15 g, and 20 g food scrap was more or less similar but always higher than blank. The most crucial observation was that beyond day 10 the amount of biogas generation declined in presence of all the different weights of food scrap, which can significantly correlated with the fact that there is a marked decline in the rate of AD beyond day 10. It was observed that between days 13 and 27; 0.157, 0.158, 0.158, 0.157 moles of biogas and 2.523, 2.532, 2.527 and 2.516 g of methane accumulated in the reactor in presence of 5 g, 10 g, 15 g, and 20 g food scrap respectively. It was also observed that the calculated methane generated with the pressure measurements is similar to the methane generated from the concentration (mg/L).

Statistical Analysis

An F-test was run to determine any significant variance in generation of methane, carbon dioxide, and pressure in presence of different weights of food scraps in the reaction medium during the 27 days of observation. The test run results indicated no significant variation in generation of biogas or pressure in the reaction medium during the different days of observation. This might have been due to the fact that the variation in the weight of food scraps (cumulative increase of 5 g) was too small to bring about a noticeable change in the quantity of pressure generation in the reaction medium during the period of study. Further studies using less than 5 g food scrap would bring in more significant information.
Table 4. Grams of methane generated during AD (Calculated using the ideal gas law)

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
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<td>Blank</td>
<td>0.3556</td>
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<td>0.3764</td>
<td>0.3788</td>
<td>0.3699</td>
<td>0.3624</td>
<td>0.3590</td>
<td>0.3573</td>
<td>0.3556</td>
<td>0.3522</td>
<td>0.3488</td>
<td>3.9824</td>
</tr>
<tr>
<td>5g</td>
<td>0.3710</td>
<td>0.3747</td>
<td>0.3789</td>
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<td>0.3659</td>
<td>0.3634</td>
<td>0.3591</td>
<td>0.3582</td>
<td>0.3545</td>
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<td>4.029</td>
</tr>
<tr>
<td>10g</td>
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<td>0.3723</td>
<td>0.3675</td>
<td>0.3628</td>
<td>0.3585</td>
<td>0.3599</td>
<td>0.3558</td>
<td>0.3547</td>
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</tr>
<tr>
<td>15g</td>
<td>0.3787</td>
<td>0.3820</td>
<td>0.3902</td>
<td>0.3796</td>
<td>0.3688</td>
<td>0.3656</td>
<td>0.3630</td>
<td>0.3603</td>
<td>0.3583</td>
<td>0.3560</td>
<td>0.3550</td>
<td>4.0575</td>
</tr>
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CHAPTER V

CONCLUSIONS

The result of our anaerobic tests showed any amount of food scrap from 5-20 g leads to an increase in biogas production.

The VS/TS ratio in the food scrap samples was found to be relatively high thus favoring anaerobic digestion process. The total carbon content of the food scraps ranged between 19-20%.

The study indicated that methane generation reached the peak, on day 8 with the production of 727, 752, 849, and 935 mg/L of methane gas (not cumulative release) in the presence of 5, 10, 15, and 20 g food waste respectively. This can be considered as the optimum time condition for the generation of methane. Most of the biogas was generated during the first 10 days. Methane accounted for ~ 80% of the total biogas produced. Lowest methane concentration (> blank) was recorded on day 3 (485 mg/L of methane) in presence of 5 g food waste whereas highest methane concentration (935 mg/L) was recorded in presence of 20 g of food waste on day 8.

F-test indicated no significant variance between the generation of methane, carbon dioxide and pressure during the different days of observation in presence of various weights of food scraps. This can be correlated to the fact that little variation in the weight of food scraps will not bring about a significant difference in the rate of methane production.
Analysis indicated that the biogas produced from the decomposition of food waste was a mixture of 76% methane and 24% carbon dioxide. Methane was observed to have a positive correlation with carbon dioxide in the presence of different weights of food scrap in the reaction medium. This indicates the simultaneous rise in both the biogas during the anaerobic digestion process.

Chico State generates a lot of food waste. According to 2007 statistics Chico State generated 2321.2 tons of total waste of which 55.4 tons was food waste diverted for composting (Eli Goodsell, Recycling Operations Coordinator, CSU, Chico, Associated Students Recycling, unpublished data, 2011). The diverted food waste was all pre consumer waste. All post consumer waste ends up in the landfills. No data are available on how much post consumer food waste is generated at Chico State. Our study shows that 935 mg/L of CH₄ is generated on day 8 in 20 g food waste sample. So if 55.4 tons of food waste were to be digested then the total methane generation would be ~259 x 10⁷ mg/L. This result suggests that food waste may be a desirable feedstock for anaerobic digestion.
CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

The result of this preliminary lab scale study shows there is a need for further in depth study focusing on certain aspects of the experiments. Some of the aspects would be as follows:

1. The food waste analyzed in this experiment was all pre-consumer food waste. If the aim is to generate more biogas then the level of putrescibility might be a key factor. The more putrescible the material (i.e., post consumer waste) the higher the gas yields possible, so it would be interesting to see how post consumer food waste, with all its fats and grease, responds in a lab scale experiment.

2. Another important aspect is the pH of the digester. It would also be interesting to see how the microorganisms react to high and low pH. Maybe one is more conducive than the other. Certain kinds of food waste might alter the pH of the digester thereby influencing production. pH of medium has a crucial impact on the overall growth/metabolism of the microorganisms. Little change in the pH of the medium alters the enzymetic activity thus generating a negative impact on the microbial growth and sustainability. Thus, a detail investigation with respect to the pH of the reaction medium would throw more light on the anaerobic digestion process.
3. A study can also be conducted to ascertain the various kinds of microorganisms in the bacterial inocula collected from the municipal waste water treatment plant in Chico to see if that has any influence on the amount of generated. A detailed understanding of the bacterial inocula will definitely be helpful.

4. Another key thing would be to determine the carbon:nitrogen ratio of the food waste to see if there is an optimal ratio the microbes prefer to have a high biogas output.

5. The experiment conducted is an initial attempt to study the rate of production by anaerobic digestion of food scraps. For further characterization of the dynamics of anaerobic digestion the experiments needs to be redone meticulously and various parameters affecting the process needs to be studied in detail.

6. The observation that methane is produced during anaerobic digestion of any food scrap in 5-20 g range may indicate that in the current experimental condition, the amount of sludge (bacterial inoculums) supplied as the seed culture, thrives well on 5 g food scrap so no extra food makes a difference. Additional “future work” should include studies using less than 5 g of food.
REFERENCES


