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Kinetic Modeling of Biogas from Food Waste: A Case Study of Ethiopian Airlines

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Abstract

When looking for sustainable energy systems that are environmentally friendly, clean and versatile, Biogas plays a significant role. Moreover, converting food waste into Biogas helps to generate energy and reduce greenhouse gas emission by avoiding food waste from going to landfill since methane is a greenhouse gas, if it is not properly handled, can create global warming. Thus, finding an alternative energy sources that are efficient and environmentally friendly is a very challenging task. However, understanding the detail phenomena inside a Biogas reactor helps to better use the full potential of Biogas. Thus, in this thesis, a detailed kinetics model has been performed. Besides, the model has been validated by using experimentally analysis. A Matlab code has also been developed to size biogas plants. Detailed ultimate analysis and proximate of the food waste has been performed by using ultimate and proximate analyzer respectively. The data has been collected and measured to be 505 kg/day food waste from Ethiopian airlines different areas like food waste returned from different flight services on the aircrafts, food waste from in-flight catering and food waste from the three cafeterias. Based on the result, a total of 20.2m^3/day biogas can be generated. Based on the result, the kinetic model has been validated by using experimental data. The result also show that the model can be used to know the real phenomena inside the reactor since the model fits with the experimental data. Thus, by producing biogas from food waste, the food waste disposal can be avoided and more than 119,000 Birr per month can be saved since Ethiopian airlines is spending this amount of money for cooking purpose. Thus, this research will solve the energy problems of Ethiopian Airlines and the biogas could be upgraded to generate electricity that is going to be used for various applications.

Keywords: Kinetic Model, Experiment, Biogas, Food Waste

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Acronyms

AD: Anaerobic Digestion

EAA: Ethiopian Aviation Academy

HRT: Hydraulic Retention Time

TS: Total Solid

VS: Volatile Solid

C/N: Carbon to Nitrogen ratio

CHONS: Carbon, Hydrogen, Oxygen, Nitrogen and Sulfur

FW: Food Waste

MSW: Municipal Solid Waste

CHP: Combined Heat and Power

VFA: Volatile Fatty Acids

Kg: Kilogram

GERD: Great Ethiopian Renaissance Dam

RT: Retention Time

Enj: Enjera

FBC: Fish, Beef and Chicken

Br: Bread

PM: Pasta and Macaroni

Veg: Vegetable

MC: Moisture Content

1.0 Introduction

1.1 Background

With the worldwide economic development and population growth, food waste is increasingly produced mainly by hotels, restaurants, families, canteens and companies like Ethiopian Airlines. The amount of food waste (FW) in Ethiopian Airlines is nearly 505 Kg/day. Food waste accounts for a large proportion in municipal solid wastes (MSW) in both of developed and developing countries.

British Airways and a group of 10 airlines around the world including American Airlines, FedEx, JetBlue, Southwest Airlines, Lufthansa and Air Canada have started building and some planned to build biogas facilities near their airports. The jet fuel that is used by major airlines is not just a pollutant; it is also the companies' biggest expense. To cut back on carbon emissions and budget, these five airlines are turning to sustainable biogas.

United Airlines: Following a $30 million investment, the largest of its kind so far by a domestic airline. United is now using biogas that is made from farm waste and animal fat oil. Currently, planes fly with a mix of 30 percent bio-fuel and 70 percent traditional jet fuel but United's plans include blending biogas into its overall supply.

Alaska Airlines: In 2011 Alaska Airlines became the first United States commercial airline to run its regularly scheduled flights using biogas derived from cooking oil. It flew 75 flights between Seattle and Washington D.C., and Seattle and Portland, with that original stock. Now, the company is setting goals to use sustainable biogas in one or more of its airports by 2020.

Southwest Airlines: The budget carrier is purchasing low carbon renewable jet fuel rendered from forest residues and its first delivery is expected next year. By collecting and using forest clippings, the company helps cut down on the risk of wildfires in the Western states. Southwest's agreement with its biogas provider includes 3 million gallons per year.

British Airways: Not only is British Airways committing to a purchase of $550 million worth of biogas, it is also providing funds and capital for the development of a facility that will turn landfill waste into renewable jet fuel. Approximately 633,800 tons of post-recycled waste will be converted to 132,270 tons of clean burning liquid fuel.

FedEx: It is not a commercial airliner, but the delivery service is making big strides in the implementation of renewable biogas. FedEx Express will purchase and use about 3 million gallons of low-carbon renewable jet fuel per year from 2017 to 2024. The biogas will be made from the same forest wood waste as Southwest Airlines'.

Biogas is produced during anaerobic digestion of organic substrates, such as manure, sewage sludge, the organic fractions of household and industry waste, and energy crops. It is produced in large scale digesters found preliminary in industrial countries, as well as in small scale digesters found worldwide. Biogas is also produced during anaerobic degradation in landfills and is then referred to as landfill gas.

In order to increase the calorific value and reduce unwanted components, e.g. CO_2, H_2S and NH_3, which are harmful to utilization systems, it is important to clean raw biogas and upgrade it to a higher fuel standard. The process is called biogas cleaning and upgrading [1, 2]. Upgrading biogas to bio-methane is one of the technologies that attract great interest in the bio-energy industry.

Biogas is a renewable energy source that can be harvested from organic wastes like the food waste. Biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2) and it can be utilized as a renewable energy source in combined heat and power plants, as a vehicle fuel, or as a substitute for natural gas. This energy release allows biogas to be used as a fuel; it can be used for any heating purpose such as cooking. It can also be used in a gas engine to convert the energy in the gas in to electricity and heat. The methane in the biogas can also be utilized in industrial processes and as a raw material in the industry. Production and utilization of biogas has several environmental advantages such as:

- It is a renewable energy source.
- It reduces the release of methane to the atmosphere compared to e.g. traditional manure management or landfills.
- It can be used as a substitute for fossil fuels.
- A high quality digestate that can be used as a fertilizer is produced simultaneously with biogas.

Waste management is very important in both urban and rural settings. Most industrialized parts of the world already have waste management systems, though they often can be improved with regards to environmental impact. Rural areas often lack sanitation or reliable waste management systems, and this is a highly valuable service for health and environmental reasons.

Anaerobic digestion can provide energy to those who do not already have it, or can produce clean energy as an alternative to carbon-intensive energy production. Energy provided to those who do not already have it enables societies to accomplish more, and allows for a much higher quality of life. Clean energy is gaining more importance as global energy consumption grows and humans have more of an impact on the global climate.

The fertilizer by-product is another benefit that can add value to an anaerobic digestion system. Once a feedstock is consumed by the anaerobic digestion process, the leftover material can be used as a soil additive to enhance crop production. In rural settings, this fertilizer is best used locally or on-site of the anaerobic digester.

Biogas produced from anaerobic digestion often has high amounts of sulfur, which is what causes an uncomfortable smell. This is only very problematic if the intent is to use the biogas in a fuel cell, because the sulfur will poison the fuel cell. There are sulfur scrubbers available to remove the sulfur if the intent is to use the biogas in a fuel cell, but this adds significantly to cost. If the gas is just to be burned as cooking fuel or in a generator, then sulfur production is not necessarily a problem [6].

1.2 Problem Statement

Upgrading of biogas has gained increased attention due to rising oil and natural gas prices and increasing targets for renewable fuel quotes in many countries. Currently in our world energy is the major concern specially the renewable energy (green energy) like the Great Ethiopian Renaissance Dam (GERD) that is causing tension between Ethiopia and Egypt. In Africa, especially in Ethiopia, renewable energy plays a vital role in boosting the country's economy by supplying the industries energy demand. As the fastest growing and most profitable airline in Africa, Ethiopian Airlines number employees is growing so fast and it has reached 12000.The amount of food waste is getting higher and higher through time, since the number of employees and passengers are growing so fast. Storage and transportation of the food waste has become very difficult.

The research will identify the effect of food waste storage and transportation of the food waste from the Ethiopian Airlines compound to the other end of Addis Ababa. CO_2 and H_2S have significant negative impacts on the utilization system, such as corrosion, increased emissions and hazards for human health.

Birds are becoming serious hazards to aviation industry. A bird or flock of birds that suddenly coming to the runway or surrounding area that collide with incoming or departing aircraft possibly resulting in an aircraft accident and loss of human life. Variety of food wastes becomes abundantly available for birds through careless waste handling and disposal and left over foods. This is causing bird strike on the aircraft body and engine.

In many countries the disposal of food waste (FW) causes severe environmental pollution, therefore, it needs an effective treatment measures. [3] The traditional approaches for food waste disposal were mainly landfill, incineration and aerobic composting. Whereas land filling food waste has been largely banned in many countries, incineration is energy-intensive (due to the high moisture content (MC)) and often creating air pollution. Both environmentally unfriendly approaches are gradually discarded. The application of food waste as animal feed also bears a lot of risks since the propagation of diseases will be higher if food waste is directly used as animal feed as a result of the shorter food chain. Laws are hence increasingly more severe with respect of environmental protection and to ensure food safety. Alternative methods for food waste disposal are needed to tackle the waste crisis.

1.3 Objectives of the Research

1.3.1 General Objective

The main objective of the research is to carryout modeling of biogas production from food wastes that will be collected from Ethiopian Airlines.

1.3.2 Specific Objective

- To determine waste generation rate.
- To characterize the food waste
- To carryout biogas generation using anaerobic digestion
- To develop kinetic model for the biogas generation
- Validation of the developed kinetic model

1.4 Significance of the Research

Ethiopian Airlines will gain an environmentally friendly alternate energy source for the cooking utilities and used as a backup electric generator when the Ethiopian Electric Agency power goes off. Ethiopian Airlines will get reliable energy source after successful completion of the research and implementation of the result. Since the electricity obtained from upgrading the biogas is new to Ethiopian Airlines the research will help as a reference for other studies, which may focus on similar issues, related to upgrading of biogas as an alternate energy source.

1.5 Scope of the Research

The research will be conducted considering the food wastes that will be collected from Main Cafeteria, Aviation Academy cafeteria and In-flight Catering. The study will be conducted using experimental design and it will be validated using Matlab coding.

2.0 Literature Review

2.1 Literature Review on Kinetic Modeling of Biogas

Jonathan Rea (2014) tries to model a biogas experiment that attempts to strike a balance between simplicity and effective biogas prediction. The purpose is not to create an entirely comprehensive model that takes all factors into account and predicts biogas output to a very high level of precision. It can, however, predict biogas output over time, instead of other simple models that assume that a reaction goes to completion. This is useful because it informs how much biogas potential is being captured by an anaerobic digester based on how long a feedstock is held inside the digester, which is determined by size and feed rate. [27]

Liang Yu et al. give another review of anaerobic digestion models, comparing between "black box" models and comprehensive complex models [23].

B. Wu, E. L. Bibeau and K. G. Gebremedhin developed a 3-D numerical simulation model based on conservation of mass, conservation of energy, and species transport that predicts biogas production from plug-flow anaerobic digesters [15]. Their work uses a first-order kinetic model that considers the ratio of carbon, hydrogen, and oxygen of the feedstock. This most basic model is useful for the initial development of the model of this project.

B. Wu, E. L. Bibeau and K. G. Gebremedhin also provide a review of many previous pieces of work. These include a model by Chen and Hashimoto that predicts gas production as a function of volatile solids, kinetic parameter, specific growth rate of bacteria, and temperature, but does not consider biochemical processes. Hill used this model and a computer analysis to determine maximum volumetric methane production, but did not use kinetics to model gas production over time. Other simple models address the effects of temperature, pH, nutrients, and toxins, but not kinetics of gas production based on biochemical reactions. Complex models such as ADM1 and a model produced by Minott include as many as 34 differential and algebraic equations or consider spatial dependence and fluid dynamics.

The IWA Anaerobic Digestion Model 1 (ADM1) is one of the most comprehensive anaerobic digestion models [22]. The highly structured model includes multiple steps describing chemical and physical processes; it considers the four steps of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and how those steps differ for input carbohydrates, proteins, and lipids. The differential and algebraic equation set has 26 dynamic state concentration variables and 8 implicit algebraic variables per reactor. It is highly accurate but requires input of many parameters and a high level of complexity.

M. Polit, et al use a mass-balance model to calculate output gaseous flow rates [20]. This paper attempts to find a balance between complicated models based on differential equations and “black box” models derived entirely from data. However, the model includes “fuzzy” logic to include pH and temperature dependence and match modeling to real-world data.

2.2 Literature Review on Anaerobic Digestion of Biogas

Currently biogas production is one of the most promising renewable energy sources in Ethiopia. Anaerobic digestion is one of the effective methods of treating food waste and it is also an effective way of generating biogas. The provision of bioenergy tackles both energy poverty and avoids polluting the environment; as a result biogas production technology has led to the development of number of biogas appliances for different purposes. Design and development of a cylindrical fixed dome bio-digester for cooking purpose was done in the condominium houses in Debiza site in Debre Markos Amhara Region. The size of biogas plant is $53m^3$ and the input materials are different wastes such as human excreta, kitchen and food wastes from a total of 357 peoples living in four buildings of 120 residents. [24]

According to Renwicketal [30], the average amount of greenhouse gas emission reduction per each domestic biogas installation was estimated to be about 5 tons of CO_2 equivalents per annum. Biogas also reduces surface and subsurface water pollution as organic waste substances are locked up in biogas digesters. Urban centers solid and liquid waste disposal problems can be resolved using biogas technology. A public site visited by about 2000 individuals per day can roughly generate $60m^3$ biogas [32]. In this regard, Gebreegziabher [31] emphasized that an aerobic fermentation in biogas digesters decomposes organic materials and wipes out pathogenic micro-organisms, and thus reduces environmental pollution.

Even though it is difficult to clearly know the exact time when biogas was introduced in to Ethiopia, Bekele [33] wrote as he himself constructed the first biogas installation in 1962 at Ambo School of Agriculture, the later Ambo College of Agriculture. The type of model for this first installation at Ambo was a batch type digester.

Dr. Anand Karve (President of ARI) [34] developed a compact biogas system that uses starchy or sugary feedstock (food waste, waste grain flour, fruits, green leaves, kitchen waste, etc.). 2 Kg of such a waste produces 500g of methane and the reaction is completed within 24 hours. The conventional biogas system, using cattle dung, sewerage, etc, use 40 Kg feedstock to produce the same quantity of methane and the system requires 40 days to complete the reaction. Thus, the new system is 800 times as efficient as the conventional biogas system.

Rasool Mahar, et al. in the analysis of waste agricultural biomass, considered a similar biochemical reaction to Wu et al for the prediction of methane potential of different waste inputs, but adding a term for nitrogen [21]. The biochemical reaction is not applied, however, to any time-dependent kinetic gas production predictions.

Seadi, et al., 2008 states that after upgrading, biogas can be utilized as vehicle fuel or injected into the natural gas network used as natural gas. The upgrading will remove all contaminants such as carbon dioxide and hydrogen sulfide, through which the content of methane will be increased from the average 50-75% to more than 95% [19]. In addition, methane and carbon dioxide produced from biogas can be utilized to produce chemical products as an alternative to fossil sources. For example, carbon dioxide can be used to produce dry ice etc… [19].

Apart from the biogas, anaerobic digestion can also convert the added feedstock into digested residue, which can be utilized as fertilizer in agriculture. The digested residue contains water, organic material, micro-organisms and various nutrients (SGC and SGA, 2008) [28]. It is found digested residue is better than raw slurry as fertilizer, since it is more homogenous, with an improved Nitrogen-Phosphorus balance and more inorganic nitrogen, and is easier accessible to the plants, thus improving the fertilization efficiency of the treated feedstock (Seadi, et al., 2008).

G. Wang, et al., 2007 provide a review on the liquid residue can also be used as pesticide for fruit trees and vegetables [29]. Qia, Zhang & Wang, 2004 and Wang, et al., 2007 also review that the clean liquid and solid residue can also be added to the feedstock to raise pigs, which can accelerate the pig’s growth [26, 29].

2.2.1 Biochemical Process of Anaerobic Digestion

Anaerobic digestion is a process of controlled decomposition of biodegradable materials under managed conditions where free oxygen is absent, at temperatures suitable for naturally occurring mesophilic or thermophilic anaerobic and facultative bacteria and archaea species, that convert the inputs to biogas and whole digestate. It consists in the biochemical degradation of complex organic matter resulting in the biogas production, which has as main constituents' methane (CH_4) and carbon dioxide (CO_2), and trace amounts of hydrogen (H_2), nitrogen (N_2), ammonia (NH_3) and hydrogen sulfide (H_2S). The significant amount of biodegradable components (carbohydrates, lipids and proteins) present in the microalgae biomass makes it a favorable substrate for the anaerobic microbial flora that can be converted into biogas rich in CH_4 [7].

The process occurs in the stomachs of animals, and the same biological process found in nature can be replicated and controlled by engineers. There are four major steps of anaerobic digestion, shown in figure 2.1 and described in detail in the following sections.

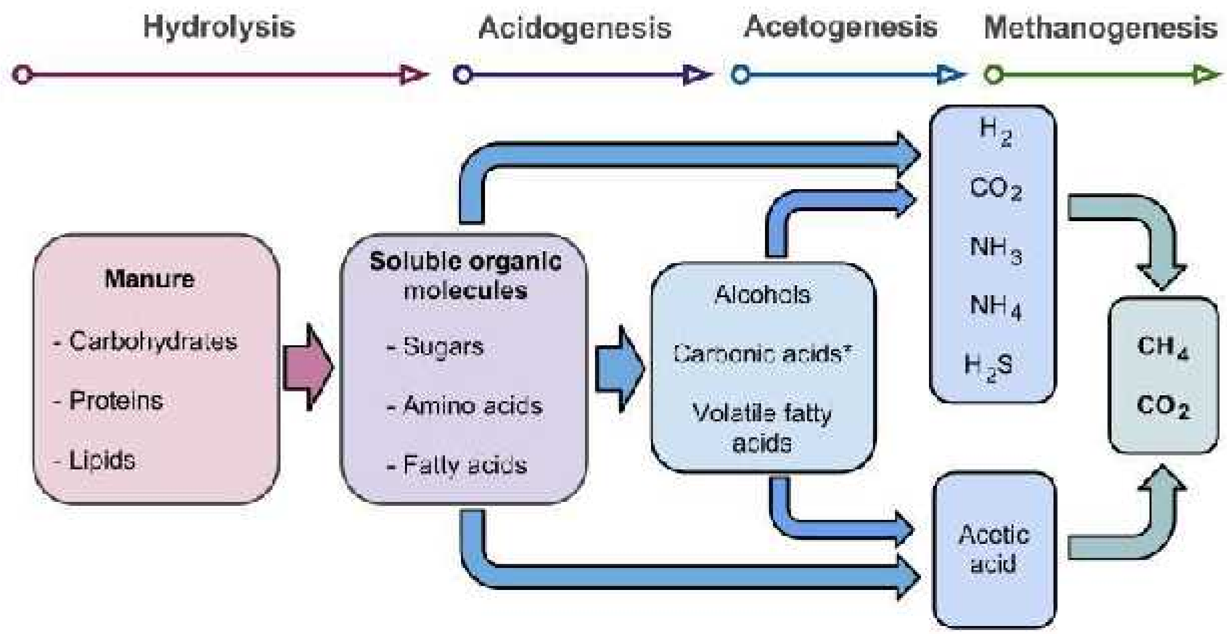

Figure 2.1: The anaerobic digestion pathway follows four major steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. [10]

Hydrolysis

In general, hydrolysis is a chemical reaction in which the breakdown of water occurs to form H+ cat-ions and OH- anions. Hydrolysis is often used to break down larger polymers, often in the presence of an acidic catalyst. In anaerobic digestion, hydrolysis is the essential first step, as food waste is normally comprised of very large organic polymers, which are otherwise unusable. Through hydrolysis, these large polymers, namely proteins, fats and carbohydrates, are broken down into smaller molecules such as amino acids, fatty acids, and simple sugars. While some of the products of hydrolysis, including hydrogen and acetate, may be used by methanogens later in the anaerobic digestion process, the majority of the molecules, which are still relatively large, must be further broken down in the process of acidogenesis so that they may be used to create methane. The digester feedstock may be made up of many different components and materials, and thus there are many different versions of hydrolysis; carbohydrates, fats, and proteins are all broken down into smaller molecules by this initial step of anaerobic digestion.

In the case of a carbohydrate, polysaccharides (complex sugars) are broken down into monosaccharide. One example is the breakdown of lactose into galactose and glucose, given in figure 2.2.

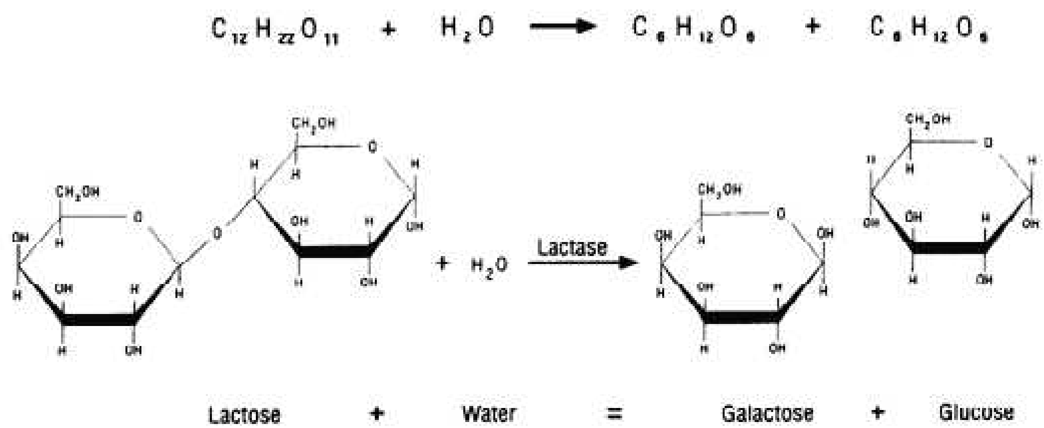

Figure 2.2: Hydrolysis breaks down lactose, a polysaccharide, into galactose and glucose, monosaccharides. [16]

In the case of lipids, usually triglycerides are split into three fatty acids and glycerol by the addition of three water molecules, as illustrated in figure 2.3.

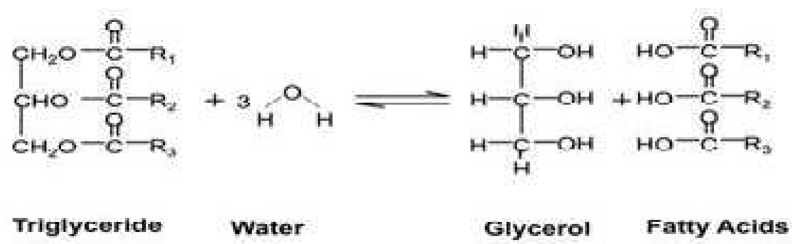

Figure 2.3: Hydrolysis of a triglyceride results in glycerol and three fatty acids. [17]

In the case of proteins, peptide bonds are broken to separate amino acids. [8, 9]

Figure 2.4: Hydrolysis of a protein involves breaking a peptide bond to separate amino acids. [9]

Acidogenesis

Acidogenesis is the next step of anaerobic digestion in which acidogenic microorganisms further break down the biomass products after hydrolysis. These fermentative bacteria produce an acidic environment in the digestive tank while creating ammonia, H_2, CO_2, H_2S, shorter volatile fatty acids, carbonic acids, alcohols, as well as trace amounts of other byproducts. While acidogenic bacteria further breaks down the organic matter, it is still too large and unusable for the ultimate goal of methane production, so the food waste must next undergo the process of acetogenesis. Acidogenesis represents the portion of figure 2.5 in which bacteria produce acetate and butyrate (volatile fatty acids) from glucose.

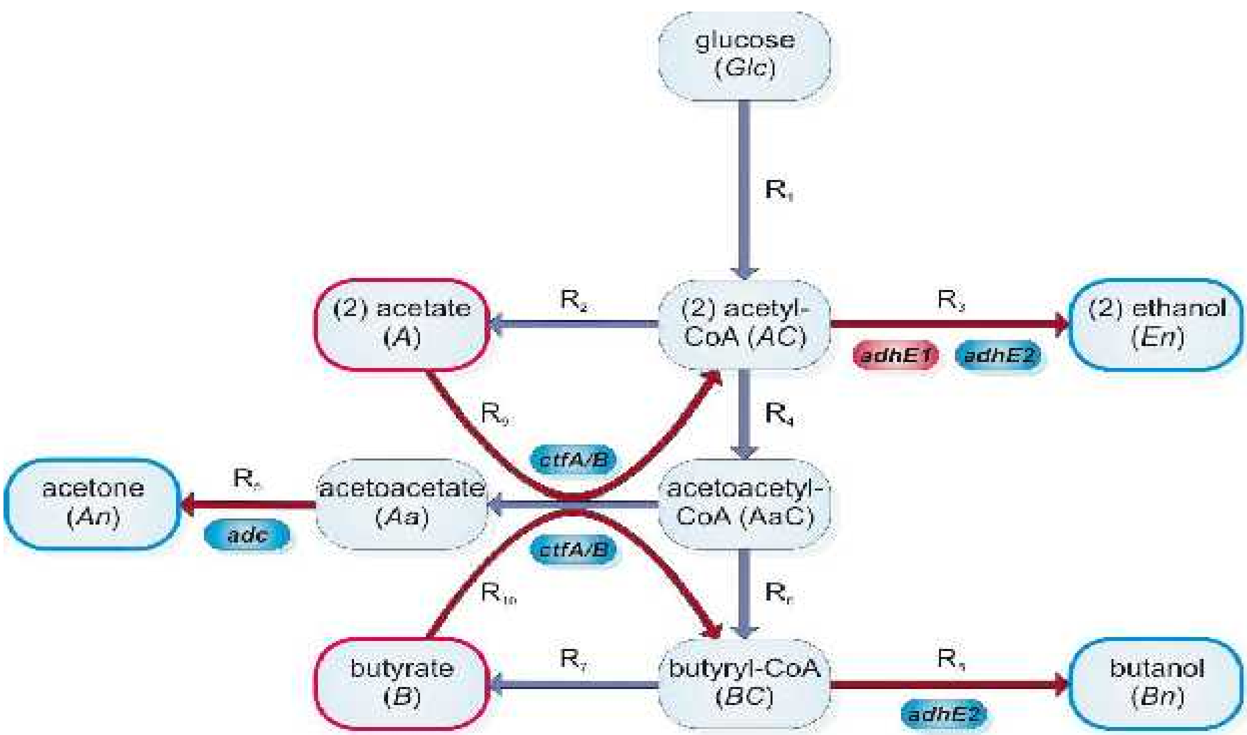

Figure 2.5: During acidogenesis, bacteria produce acetate and butyrate (bordered with red edges). The fermentive pathway can also produce other by-products. [18]

Acetogenesis

In general, acetogenesis is the creation of acetate, a derivative of acetic acid, from carbon and energy sources by acetogens. These microorganisms catabolize many of the products created in acidogenesis into acetic acid, CO_2 and H_2. Acetogens break down the food waste to a point to which methanogens can utilize much of the remaining material to create methane as a biofuel. In the third step of anaerobic digestion, acetogenic bacteria consume precursors and produce acetate (acetic acid). One example of this process is the consumption of glucose, given in equation 1. [10]

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (1)$$

Methanogenesis

The final step of anaerobic digestion is for the most part, the biological process here is the breakdown of acetic acid, given in equation 3, though other forms of the reaction can also produce methane via anaerobic digestion. Methanogenesis constitutes the final stage of anaerobic digestion in which methanogens create methane from the final products of acetogenesis as well as from some of the intermediate products from hydrolysis and acidogenesis. The formation of methane by bacteria called methanogens. There are two general pathways involving the use of acetic acid and carbon dioxide, the two main products of the first three steps of anaerobic digestion, to create methane in methanogenesis:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (3)$$

While CO_2 can be converted into methane and water through the reaction, the main mechanism to create methane in methanogenesis is the path involving acetic acid. This path creates methane and CO_2, the two main products of anaerobic digestion.

2.2.2 Parameters that Influence Biogas Production

There are other parameters that influence the biogas production from an anaerobic digester depends on the ability of bacteria to thrive inside the digester. The bacteria survives inside a biogas digester depends on the temperature, pH, total solid, volatile solid, C/N ratio and physical conditions of the anaerobic digester.

pH

The survival of methanogenic bacteria also depends on the acidity of the environment that they are in methanogenesis requires a near-neutral pH (between 6.5 and 7.5). A decrease in pH can inhibit gas production and can lead to further accumulation of acids [14]. Methanogenic activities may be stopped or inhibited if the pH is lower than 6, because hydrogen production occurs instead of methane production. If pH is lower than 6.5 all the process could be stopped. However, CO_2 as carbonic acid and ammonia avoids either strong acidification or basification due to act as buffering system. $CaCO_3$ is used as alkaline to control the pH. Alkalinity can be increased by adding chemicals like MgO, $NaHCO_3$, NaOH, NH_3 and Na_2CO_3.

Total Solid

The total solid (TS) test determines how much of the food waste is composed of water and how much of the food waste is solid. The food waste samples were homogenized in a blender and the mass of each sample was measured and recorded. The samples were then placed in an oven set to 105°C for a period of at least 24 hours and weighed.

Volatile Solid

The sample which was dried in the total solid method was placed in a furnace at a temperature of 550°C for at least 4 hours. After cooling in a desiccator, the sample was weighed. This test determines how much of the dry matter is composed of volatile organic material. The resulting residue is composed of inorganic material.

Temperature

Temperature is one of the basic parameters that affect the survival of the bacteria inside the digester. The three digestion types of temperature ranges are named psychrophilic digestion, mesophilic digestion and thermophilic digestions. Psychrophilic digestion occurs at below 25 °C, or below room temperature. Mesophilic digestion occurs between 25 and 45 °C, while thermophilic digestion occurs above 45 °C [11]. Biogas production under thermophilic (55 °C) condition is more than double the output under psychrophilic (15 °C) condition. In general, higher temperatures result in higher biogas production. Further, rapid temperature changes can upset bacterial activity, so for experimental studies, it is important that temperature is held constant [12]. With increase in temperature the toxicity of H_2S increases.

Table 2.1: Summary of Temperature ranges (Jay Cheng 2009) and (Deublein, D. et al. 2008)

Anaerobic Process	Operating Temperature (ºC)	Operating (days)	Microbial Growth and Digestion Rates	Tolerance to Toxicity
Psychrophilic	10-25	>50	Low	High
Mesophilic	25-45	25-30	Medium	Medium
Thermophilic	45-65	10-15	High	Low

C/N Ratio

The production of biogas can also be influenced by the relative amount of organic carbon and nitrogen in the feedstock, which is measured as Carbon/Nitrogen (C/N) ratio. A low C/N ratio can lead to pH values above 8.5, while a high C/N ratio may result in lower methane production rates.

Mixing and Other Physical Conditions

Contact between bacteria and the slurry that they are consuming is vital to the anaerobic digestion process. One way to maximize this contact is to keep the digester thoroughly mixed at all times.

Methanogens naturally live inside the stomachs of animals, and attach to the stomach lining as a way to secure a safe habitat with a steady supply of food. When placed inside of a man-made anaerobic digester, instead of floating around in the slurry, the bacteria attach to surfaces while being exposed to the flow of digestible material [13]. Some anaerobic digester designs address this issue by creating internal structures so that bacteria can attach to them and be exposed to more digestible material. Otherwise, mixing is an important design parameter in maximizing anaerobic digestion performance because it allows enhanced contact between bacteria and the material being consumed.

2.2.3 History and Use of Anaerobic Digestion

The generation of combustible gas from decomposing organic matter has been known for decades. In 1776, Volta determined that the amount of organic material and the amount of gas produced were directly connected. John Dalton and Humphrey Davy established that the combustible gas was methane in 1804-1808. Anaerobic digestion was applied to a septic tank in 1881, and has since been applied to wastewater treatment at much larger scales. In developing countries where energy production is generally uncommon and more expensive, anaerobic digestion has more relevance in the absence of other energy sources. Notably, India is credited for having built the first-ever anaerobic digester in 1897, using human waste to meet lighting needs. Intensive plant design and technology research began in the 1950s, and the application of anaerobic digestion has grown over time. [7]

Anaerobic digestion (AD) of food waste (FW) is a complex process that should simultaneously digest all organic substrates (e.g. carbohydrate and protein) in a single-stage system. It is governed by different key parameters such as temperature, volatile fatty acids (VFA), pH, ammonia (NH_3), total solid(TS), volatile solid(VS), nutrients, trace elements, and others: a good nutrient and trace element balance, and a stable environment are required for microbial growth. It is therefore, extremely important to maintain the key parameters within the appropriate range for long term operation of anaerobic digestion.

Table 2.2: Composition of biogas [11]

Compound	Chemical Symbol	Content (Vol. %)
Methane	CH_4	50 - 75
Carbon dioxide	CO_2	25 - 45
Water vapor	H_2O	2(20^oC) - 7(40^oC)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulfide	H_2S	<1

Applications and Scales

Anaerobic digesters are very useful in aviation industries like Ethiopian Airlines, given that they take inputs of food wastes and produce biogas and energy. They are also useful in agricultural settings to produce energy and fertilizer which can both be used at these sites. They can be designed to take in virtually any type of organic waste, including plant matter, animal excrement, and by-products of industrial processes. Anaerobic digesters range in size from as small as taking in the food scraps from one family to as large as entire wastewater treatment plants for a large city.

Depending on the end use, different biogas treatment steps are necessary. For some applications, where it is important to have a high energy content in the gas, e.g. as vehicle fuel or for grid injection, the gas needs to be upgraded. The energy content of biogas is in direct proportion to the methane concentration and by removing carbon dioxide in the upgrading process the energy content of the gas is increased. Upgrading of biogas has gained increased attention due to rising oil and natural gas prices and increasing targets for renewable fuel quotes in many countries new plants are continually being built.

The process of upgrading biogas generates new possibilities for its use since it can then replace natural gas, which is used extensively in many countries. However, upgrading add to the costs of biogas production. It is therefore important to have an optimized upgrading process in terms of low energy consumption and high efficiency giving high methane content in the upgraded gas. It is also very important to minimize, or if possible avoid, emissions of methane from the upgrading process, since methane has a greenhouse gas effect 23 times greater than that of carbon dioxide. This means that the methane content in the reject gas, in the water from a water scrubber, or in any other stream leaving the upgrading plant should be minimized.

3.0. Material and Method

3.1 Materials

The food waste obtained for experimental evaluation was taken from Ethiopian Airlines different cafeterias and returned food wastes from different flights. There are six different food waste samples:

1. Enjera with Wot(Enj)
2. Fish, Beef and Chicken(FBC)
3. Bread(Br)
4. Pasta and Macaroni(PM)
5. Rice
6. Vegetable(Veg)

Figure 3.1: Fish, Beef and Chicken

Figure 3.2: Bread

Figure 3.3: Vegetable

Figure 3.4: Enjera with Wot

Figure 3.5: Pasta and Macaroni

Figure 3.6: Rice

The food waste samples were collected and transported to Addis Ababa Institute of Technology, Chemical Engineering Department laboratory. The biogas production experiment from food waste and total solid and volatile solid analysis were conducted in Addis Ababa Institute of Technology, Chemical Engineering Department laboratories.

Weighing balance, pH meter, gas analyzer, furnace and water bath are some of the major equipment's used for the experimental work.

3.2 Methods

3.2.1 Density of Food Waste

The food waste density was measured by determining the volume of a given mass of food waste. An Erlenmeyer flask is placed on a scale and initially filled with water. Food waste is placed into the flask; its volume is determined by the amount of displaced liquid in the flask, and its mass is determined by the change in mass observed on the scale. To get a refined result the measurement is taken three times and measured values and calculation of density of the food waste are given in table 3.1. Density is calculated as the ratio of mass to volume, and is found to be 1.12 $\pm$ 0.01 Kg/L. The density of water is a standard value which is 1000Kg/m^3 = 1 Kg/L.

Table 3.1: Density of Food Waste (Kg/L)

Mass of sample (g)	Volume of sample (mL)	Density of sample (Kg/L)
50	44. 64	1.12
55	49.55	1.11
60	53.10	1.13

3.2.2 Analysis Methods

Analyses were done in duplicate with the same temperature and pH. During the biogas production the pH, temperature, chemical composition, total solid (TS) and volatile solid of the food waste were initially measure and determined.

Instruments Used

During the experiment different instruments were used:

- **pH Meter**: used to measure the pH of the food wastes. The food wastes have pH of 7.59 and the samples were done in duplicate.
- **Thermometer**: used to measure the external water bass temperature and internal temperature inside the plastic flask.
- **Weighing Scale**: used to measure the mass of food wastes.
- **Gas Analyzer**: used to measure the chemical composition of the biogas produced in the form of methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S) and ammonia NH_3.
- **Water bass**: gives maintained temperature to the samples inside the plastic flask
- **Air bags:** holds the biogas produced from the food waste anaerobically.
- **Vacuum Pump**: this pump was used to purge the air inside the air bag. The vacuum pump has a great contribution for anaerobic digestion of the food waste.
- **Flask**: works as an aerobic digester for a laboratory purpose
- **Oven:** used to dry food waste samples which were placed inside it and its temperature is set to 105°C for a period of at least 24 hours and finally the food waste samples will be weighed.
- **Furnace:** used to heat the samples at a temperature of 550°C for at least 4 hours which was dried in an over using the total solid method.

3.3 Kinetic Modeling of Anaerobic Digestion

3.3.1 Purpose of this Model

This model attempts to strike a balance between simplicity and effective biogas prediction. The purpose is not to create an entirely comprehensive model that takes all factors into account and predicts biogas output to a very high level of precision. It can, however, predict biogas output over time, instead of other simple models that assume that a reaction goes to completion. This is useful because it informs how much biogas potential is being captured by an anaerobic digester based on how long a feedstock is held inside the digester, which is determined by size and feed rate.

3.3.2 Model Assumptions

The initial assumptions of this model are given in bullet form below.

- Constant temperature
- Constant digester volume
- Perfect mixing
- Ideal bacterial conditions, meaning full digestion
- Input waste consists of only C, H, O, N and S
- Products of reaction include only CH_4, CO_2, NH_3 and H_2S
- No accumulation of ashes

3.3.3 Basic Input-Output Model and Biochemical Equations

In the simplest case of a well-stirred single tank reactor, reactants A and B are put into the digester at a certain rate (in the model, this value is specified by a user input). Once in the digester, A and B break down into products C and D at a rate based on reaction coefficients. Some of A and B don't break down all the way, and leave through the outlet - the amount that leaves instead of being broken down depends upon digester size and feeding rate, which determine the residence time of the feedstock.

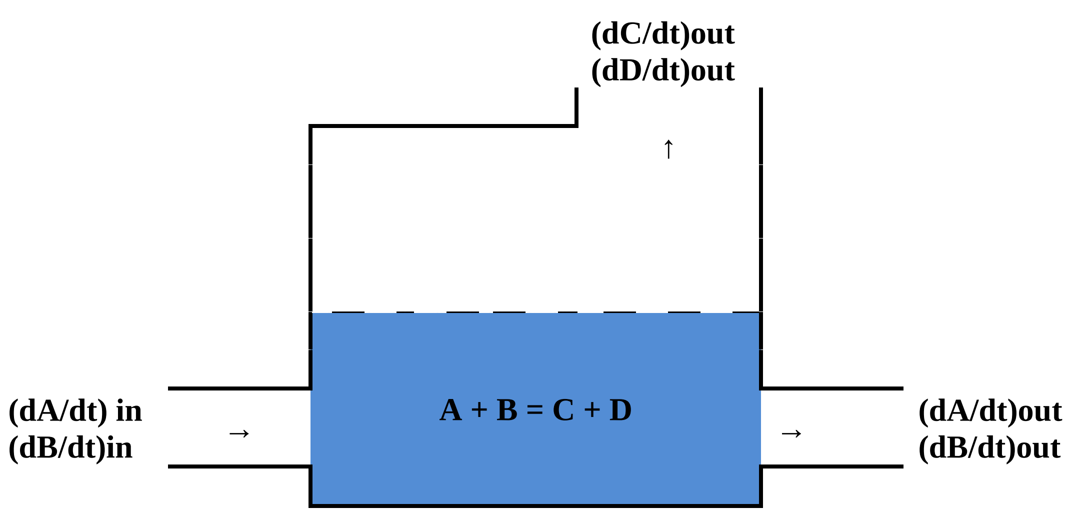

Figure 3.7: Basic input-output model of a well-stirred single tank reactor. This simple process is used for the kinetic model of this work.

3.3.4 Food Waste as Anaerobic Digestion Substrate

Waste analysis is one of the most important steps in the anaerobic digestion process. Knowing the general composition of the input material to the system is essential for calculating the amount and composition of the biogas produced as well as the amount of energy contained in the biogas.

Anaerobic degradability greatly depends on the composition of the input material considered. It's very difficult to estimate or measure the percentage of carbohydrates, lipids, and proteins in a heterogeneous substrate such as food waste due to the dynamic and sensitive nature of the biological process to the input composition. There are several techniques available to estimate the amount of biogas contained in a complex substrate such as food waste including ultimate analysis, computer simulation, and a literature review of experimentally determined biogas yields.

Elemental Analysis of Food Waste for Biogas Production

This technique of biogas estimation involves breaking food waste down into its elemental composition of carbon, hydrogen, oxygen, nitrogen and sulfur. The elemental analysis of the food waste was done in 4 kilo chemistry laboratory and elemental composition of the FW is listed in Table 3.2.

Number of Sample: 1
Analysis: Elemental analysis: CHONS
Device: EA 1112 Flash CHONS - analyzer
Conditions: Carrier gas flow rate of 120 ml/min, reference flow rate 100 ml/min, oxygen flow rate 250 ml/min; furnace temperature of 900 ºC and oven temperature of 75 °C.

Calibration: 4 calibration points for every component. Samples were run in duplicate and the average values are reported. The elemental analysis of food waste will help us identify chemical composition of the food waste.

Table 3.2: Elemental analysis of food waste

FW Elemental Composition	%
C	45.405
H	7.655
O	42.915
N	3.945
S	0.4

The biochemical reaction equation used for this analysis is taken from Wu et al [15], and is reproduced in the below equation

$C_nH_aO_bN_cS_d + c_1H_2O = c_2CO_2 + c_3CH_4 + c_4NH_3 + c_5H_2S$ (4)

Where,

C: $n = c_2 + c_3$ (5)

H: $a + 2c_1 = 4c_3 + 3c_4 + 2c_5$ (6)

O: $b + c_1 = 2c_2$ (7)

N: $c = c_4$ (8)

S: $d = c_5$ (9)

Where,

$c_1 = n – a/4 – b/2 + (3/4)*c + d/2$ (10)

$c_2 = n/2 – a/8 + b/4 + (3/8)*c + d/4$ (11)

$c_3 = n/2 + a/8 - b/4 - (3/8)*c - d/4$ (12)

$c_4 = c$ (13)

$c_5 = d$ (14)

The biochemical reaction is automatically balanced and can be applied to any input with known relative ratios of carbon, hydrogen, and oxygen. The model assumes that these elements are the only components of the feedstock.

Table 3.3: Balance of biochemical reaction

	Left	Right
C	.n	n/2 + n/2 = n
H	a + 2*[n – a/4 – b/2 + (3/4)*c + d/2] = 2n + a/2 - b + (3/2)*c + d	4[n/2 + a/8 - b/4 - (3/8)*c - d/4] + 3c + 2d = 2n + a/2 -b + (3/2)*c + d
O	b + [n – a/4 – b/2 + (3/4)*c + d/2] = n –a/4 + b/2 + (3/4)*c + d/2	2*[n/2 – a/8 + b/4 + (3/8)*c + d/4] = n –a/4 + b/2 + (3/4)*c + d/2
N	.c	.c
S	.d	.d

Molar Ratios and Coefficient Calculations

The mass ratios is converted to molar ratios in order to determine the constants n, a, b, c and d for the feed stock $C_nH_aO_bN_cS_d$ to get the ultimate analysis. Ultimate analysis gives mass ratios of C:H:O:N:S (in grams) which are then defined as variables nbymass : abymass: bbymass: cbymass: dbymass. Where :

nbymass = 0.45405

abymass = 0.07655

bbymass = 0.42915

cbymass = 0.03945

dbymass = 0.004

Then, for molar masses of carbon (mm_C), hydrogen (mm_H), oxygen (mm_O), nitrogen(mm_N) and sulfur (mm_S) we have:

$$n = \frac{nbymass}{mm_C} = \frac{nbymass}{12.0107} \quad (15)$$

$$a = \frac{abymass}{mm_H} = \frac{abymass}{1.0079} \quad (16)$$

$$b = \frac{bbymass}{mm_O} = \frac{bbymass}{15.999} \quad (17)$$

$$c = \frac{cbymass}{mm_N} = \frac{cbymass}{14.0067} \quad (18)$$

$$d = \frac{dbymass}{mm_S} = \frac{dbymass}{32.065} \quad (19)$$

The constants c_1, c_2, c_3, c_4 and c_5 are then calculated using equations 10, 11, 12, 13 and 14. The molar masses of each reactant and product can then also be calculated using the below listed equations:

$$mm_A = mm_C *n + mm_H *a + mm_O *b+ mm_N *c+ mm_S *d$$

$$= 12.0107n + 1.0079a + 15.999b + 14.0067c + 32.065d \quad (20)$$

$$mm_B = 2* mm_H + mm_O$$

$$= 18.0148 \text{ g/mol} \quad (21)$$

$$mm_C = mm_C + 2* mm_O$$

$$= 44.01 \text{ g/mol} \quad (22)$$

$$mm_D = mm_C + 4* mm_H$$

$= 16.04$ g/mol (23)

$mm_E = mm_N + 3^* \, mm_H$

$= 17.0304$ g/mol (24)

$mm_F = 2^* \, mm_H + mm_S$

$= 34.0808$ g/mol (25)

3.3.5 Data Collected from Ethiopian Airlines

The food wastes were collected from different section of Ethiopian Airlines by assigning responsible person for each section and for each shift schedule by communicating with their respective supervisors and managers. Ethiopian Airlines operates 24 hours a day and seven days a week, therefore, returned food wastes were measured on every work shift on a daily basis. The collected data are listed from Table 3.4 to Table 3.7. Detailed food waste collected data are listed on appendix 4.

Table 3.4: Total Ethiopian Airlines Food Wastes

Item No	Days	Weight (Kg)
1	Monday	533
2	Tuesday	536
3	Wednesday	526
4	Thursday	518
5	Friday	473
	Total	2586

Table 3.5: FW from Main Cafeteria

Item No	Days	Weight (Kg)
1	Monday	246
2	Tuesday	306
3	Wednesday	217
4	Thursday	263
5	Friday	207
	Total	1239

Table 3.6: FW from In-flight Catering

Item No	Days	Weight (Kg)
1	Monday	287
2	Tuesday	230
3	Wednesday	309
4	Thursday	255
5	Friday	266
	Total	1347

Table 3.7: The average food waste composition of Ethiopian Airlines

Item No	FW Type	Weight(Kg)	%
1	Enjera with Wot	923	36%
2	Vegetable	487	19%
3	Pasta and Macaroni	143	5%
4	Rice	594	23%
5	Bread	81	3%
6	Fish, Beef and Chicken	358	14%
	Total	2586	

The average food waste that is collected from the Ethiopian Airlines is 505 Kg per day.

3.3.6 Gas Consumption of Ethiopian Airlines

Main Cafeteria

1441 liters of gas per three weeks, which is 37539 Birr per three weeks and this is approximately equals to 50052 Birr per month. [36]

EAA (Ethiopian Aviation Academy) Cafeteria

2000 liters per three months, which is 52101 Birr per three month and this is approximately equals to 17367 Birr per month. [36]

In-flight Catering

2000 liters per month which is approximately equals to 52101 Birr per month.

The average gas consumption from the three cafeterias is 119520 Birr per month. This amount of money could be saved by converting the food waste to biogas. [36]

4.0 Result and Discussion

4.1 Experimental Result

The experimental evaluation of the anaerobic digestion process of food waste will help us compare result of the predicted gas output from the kinetic model. Food waste is collected from Ethiopian Airlines different areas and brought to Addis Ababa Institute of Technology, Chemical Engineering Laboratory. Gas production is measured and used to adjust parameters of the model. The purpose of the experiment is to identify the amount of biogas production from 505 Kg/day of food waste.

4.1.1Experimental Model 1

On the first experimental model the food waste samples were putted in to an enclosed flask. 14 sample food waste to biogas production set-ups were done based on 1:1 and 1:2 ratio. For the 1:1 ratio 150 grams of food waste is combined with 150 grams of water and the same goes to 1:2 ratios which is 150 grams of food waste is combined with 300 grams of water. The total weight for 1:1 ratio is 300 grams and that of 1:2 is 450 grams. The mixture sample is a combination of FBC, Br, Veg, PM, Enj and Rice. The volume and quality of the biogas produced at 40 ^{o}C external and 38 ^{o}C internal (flask) temperatures were determined and recorded in table 4.1.

Table 4.1: Biogas Production of experimental model 1

Item No	Description	Ratio	Biogas production (ml)
1	Mixture	1:1	500
2	FBC	1:1	500
3	Br	1:1	200
4	Rice	1:1	50
5	Enj	1:1	100
6	PM	1:1	250
7	Veg	1:1	100
8	Mixture	1:2	800
9	FBC	1:2	600
10	Br	1:2	400
11	Rice	1:2	60

12	Enj	1:2	80
13	PM	1:2	250
14	Veg	1:2	930

Chemical compositions for the above food waste samples were measured and all of the samples produced poor quality of methane. The chemical compositions were determined more than three times in three days interval and the results were almost the same. Chemical compositions for three food waste samples are displayed in table 4.2.

Table 4.2: Quality of methane produced for three FW samples

Item No	Chemical Composition	FBC 1:2	Br 1:1	Mix 1:2
1	CH_4 (%)	0.1	0.21	0.1
2	CO_2 (%)	36.5	41.8	50.7
3	O_2 (%)	8.7	4.1	8.2
4	H_2S (ppm)	319	39	232
5	Balance (%)	54.6	54	40.6

Possible Causes why the Experiment Failed

The experiment was not successful as it was expected because of the below listed possible causes

- TS and VS was not measured instead 1:1 and 1:2 ratios were assumed
- Imperfect mixing
- pH of the food wastes were not identified or measured
- The samples were not air tight

4.1.2 Experimental Model 2

On the second experimental model pH of the food wastes were determined and recorded accordingly. On this second experimental model also 14 sample food wastes to biogas production set-ups were done based on 1:1 and 1:2 ratio. The total weight for 1:1 ratio is 300 grams and that of 1:2 is 450 grams. The mixture sample is a combination of FBC, Br, Veg, PM, Enj. and Rice.

The volume and quality of the biogas produced at 40^oC external and 38^oC internal (flask) temperature was determined and recorded in table 4.3:

Table 4.3: Biogas Production of experimental model 2

Item	Description	Ratio	pH	Biogas production
1	Mixture	1:1	5.46	420
2	FBC	1:1	5.52	660
3	Br	1:1	6.02	320
4	Rice	1:1	5.31	120
5	Enj	1:1	4.50	170
6	PM	1:1	6.92	360
7	Veg	1:1	4.83	210
8	Mixture	1:2	5.41	650
9	FBC	1:2	5.49	810
10	Br	1:2	6. 65	380
11	Rice	1:2	5.40	140
12	Enj	1:2	4.75	390
13	PM	1:2	7.01	510
14	Veg	1:2	4.88	620

Figure 4.1: The 14 Sample Experimental Food Wastes setup

Chemical compositions of the second experimental model food waste samples were determined. The quality of methane for this experimental model was not also good. The chemical compositions were measured more than three times in three days interval and the results were almost the same. Chemical compositions for three food waste samples are displayed in table 4.4.

Table 4.4: Quality of methane produced for three FW samples

Item No	Chemical Composition	FBC 1:2	Br 1:1	Mix 1:2
1	CH_4 (%)	2.5	2.1	2.6
2	CO_2 (%)	4.8	31.8	43.7
3	O_2 (%)	5.9	6.5	3.2
4	H_2S (ppm)	10	79	82
5	Balance (%)	86.8	43	36

Possible Causes why the Experiment Failed

The experiment was not successful as it was expected because of the below listed possible causes

- TS and VS was not measured instead 1:1 and 1:2 ratios were assumed
- Imperfect mixing
- The samples were not air tight

4.1.3 Experimental Model 3

The third and the final experimental models are done reassessing the previous two experimental models. On this experimental model, only two samples were taken and they are mixture of the six food waste samples which are FBC, Br, Veg, PM, Enj and Rice. Two of the experimental model samples have pH 7.59.

Table 4.5: TS and VS of Food Waste

Food Waste TS and VS						
Description	Crucible Wt.(g)	Crucible + Sample Wt.(g)	Crucible + Sample Wt.(g) at (105^{o}C)	Crucible + Sample Wt.(g) at (550^{o}C)	TS (%)	VS (%)
Mixture A	48. 51	94.99	62.33	48.99	29.73	88
Mixture B	48.91	99.40	64.53	49.43	30.93	89
Average	48.71	97.195	63.43	49.21	30.33	88.5

Table 4.6: TS and VS of Inoculum

Inoculum TS and VS						
Description	Crucible Wt.(g)	Crucible + Sample Wt.(g)	Crucible + Sample Wt.(g) at (105^{o}C)	Crucible + Sample Wt.(g) at (550^{o}C)	TS (%)	VS (%)
Mixture A	53.65	98.17	56.59	54.32	6.60	77
Mixture B	48.51	102.25	52.09	49.42	6. 66	74
Average	51.08	100.21	54.34	51.87	6. 63	75.5

- Initial TS = 30.33%
- Final TS = 9%, the final TS has to be below 10 % in order in to reduce the risk of excessive ammonia buildup.
- Sample before water (g) = 48.71
- Water to be added = $\frac{(30.33\% - 9\%)}{9\%}$ * Sample before water

  = 115.44g

The volume and quality of the biogas produced at 40 ^{o}C external and 38 ^{o}C internal (flask) temperatures and pH of 7.59 was determined and recorded in table 4.7.

Table 4.7: Biogas Production of Mixture A and B

Date	Description	Chemical Composition of Biogas					Volume of Biogas Produced $(m^3)x1o^{-6}$	Average Volume of Biogas Produced $(m^3)x1o^{-6}$
		CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	Bal (%)		
30-10-16	Mixture A	26	72	2	135	0	800	900
	Mixture B	20.1	74	5.8	135	0	1000	
01-11-16	Mixture A	34.6	60.3	5.1	46	0	1100	1150
	Mixture B	39.6	52.3	8	187	0	1200	
03-11-16	Mixture A	57.2	38	4.8	79	0	1450	1430
	Mixture B	70.7	28	1.3	82	0	1410	
05-11-16	Mixture A	60	36.7	3.3	61	0	1720	1830
	Mixture B	71.6	27.1	1.3	82	0	1940	
08-11-16	Mixture A	65.3	29.7	4.9	47	0	2200	1990
	Mixture B	71	26	3	20	0	1780	
11-11-16	Mixture A	77.2	23.4	0.5	1	0	2140	2000
	Mixture B	72.3	25.4	2.1	16	0	1860	
15-11-16	Mixture A	78.6	19.4	1.1	12	0	1820	2010
	Mixture B	71.2	26.6	2.5	1	0	2200	
20-11-16	Mixture A	77	22.1	0.8	10	0	1880	2030
	Mixture B	65.4	30.3	4	7	0	2180	
24-11-16	Mixture A	78.2	20.7	1.1	7	0	1990	2030
	Mixture B	62.7	33.3	3.9	4	0	2070	

Chemical compositions of the third experimental model on the mixture A and B food waste samples were measured. The quality of methane for this experimental model was fruitful and successful. The chemical compositions were measured twice and sometimes three times a week and measured results is displayed in the table 4.7.

Experimental setup for mixture A and B, experimental model 3, was done at pH approximately 7.6 and at 38 and 40 ^oC internal and external temperature respectively.

Figure 4.2: Experimental Setup of Mixture A and B

Kinetic model and experimental data for the duplicate 0.0487 Kg of food waste samples that were done in the laboratory is displayed in fig. 4.3. The kinetic model predicted values and the experimental result that was obtained from the laboratory setup are in agreement and it is demonstrated in fig. 4.3.

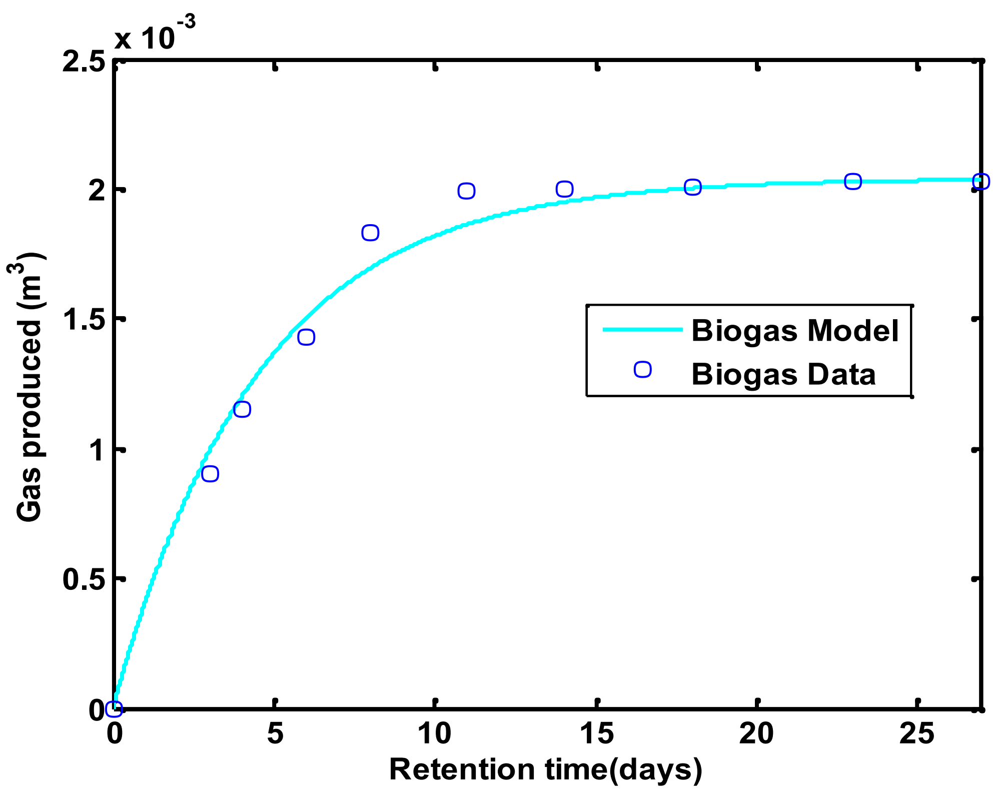

Figure 4.3: Kinetic model Vs Experimental result of the sample food wastes

Small scale experimental analyses were done on the third experiment and it was done using 0.0487 Kg food waste for each samples. A kinetic model is developed to scale up this experimental result to predict the gas produced from the 505Kg per day food waste. The kinetic model result for the 505Kg food waste is displayed in fig. 4.4.

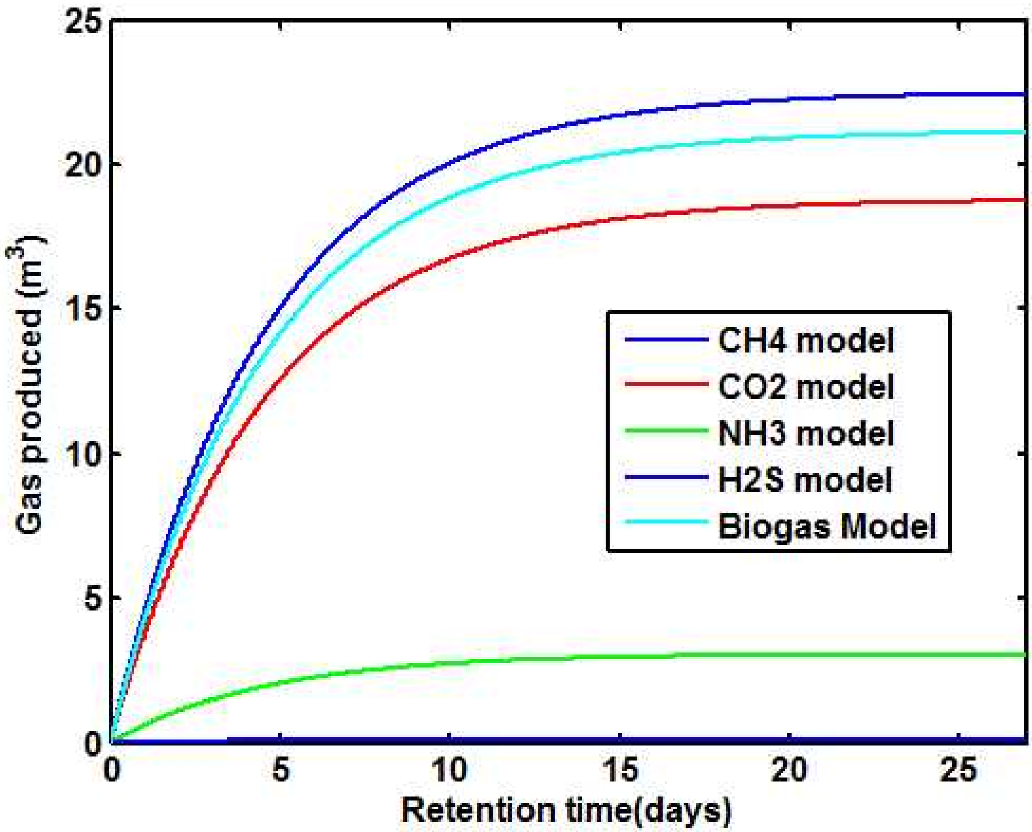

Figure 4.4: Kinetic model of 505 Kg daily input food waste

4.2 Digester Design

4.2.1 Digester Selection

An aerobic digester is a specially designed digester which is an air proof reactor tank and it is the core of a biogas system. Feedstock is decomposed in absence of oxygen in the digester, where biogas is produced. Besides, all digesters have a system to feed in feedstock and a system to output biogas and digested residue [19].

Nowadays, there are many types of digesters available in the world. The size of biogas plant can vary from a small household system of few cubic meters to a large commercial plant of several thousand cubic meters, often with several digesters [19].

The design and type of digester is determined by the dry matter content of the substrate, which is usually classified into wet digestion and dry digestion. The former is fed with dry matter content lower than 15%, while the latter between 20 and 40% [19]. Wet digestion often involves manure and sewage sludge, while dry digestion is usually applied to solid animal manure, energy crops etc.

Digester can also be classified into two types: batch and continuous, according to the feedstock input and output. Batch-type digester is the simplest to build and usually applied for dry digestion. The digester is filled at once, and then is completely removed after the feedstock digests. In a continuous-type digester, the feedstock is continuously added and the digested material is continuously removed. Compared with batch-type digesters, continuous digesters produce biogas without interruption [19].

According to the source of the feedstock, the biogas plants can be categorized into agricultural biogas plants, waste water treatment plants, municipal solid waste treatment plants, industrial biogas plants and landfill gas recovery plants etc. [19]. The agricultural biogas plants are processing feedstock of agricultural origin, which can be further divided into family scale biogas plants, farm scale biogas plants and centralized or joint co-digestion plants, based on the relative size, function and location [19].

Fixed dome and floating drum plants are the common digester types which are currently in use. Fixed dome plants are made entirely below the ground saving space and being less affected by damage and daily temperature fluctuations. The fixed dome digesters are commonly built in areas which have hotter climate weather. The floating drum plants digesters are expensive since the gas holder is made of stainless steel, but its operation is easy to understand than fixed dome plants because the gas holder is found above the ground.

4.2.2 Sizing of Digester

The anaerobic digester sizing is determined by the amount of food waste per day (daily feed), the retention time and volume of the digester. The biogas plant size is dependent on the average daily feed stock and expected hydraulic retention time of the material in the biogas system. Capacity of the plant should be designed based on the availability of raw materials. Capacity of the plant indicates the quantity of gas produced in a day.

Cross-Section of a Digester:

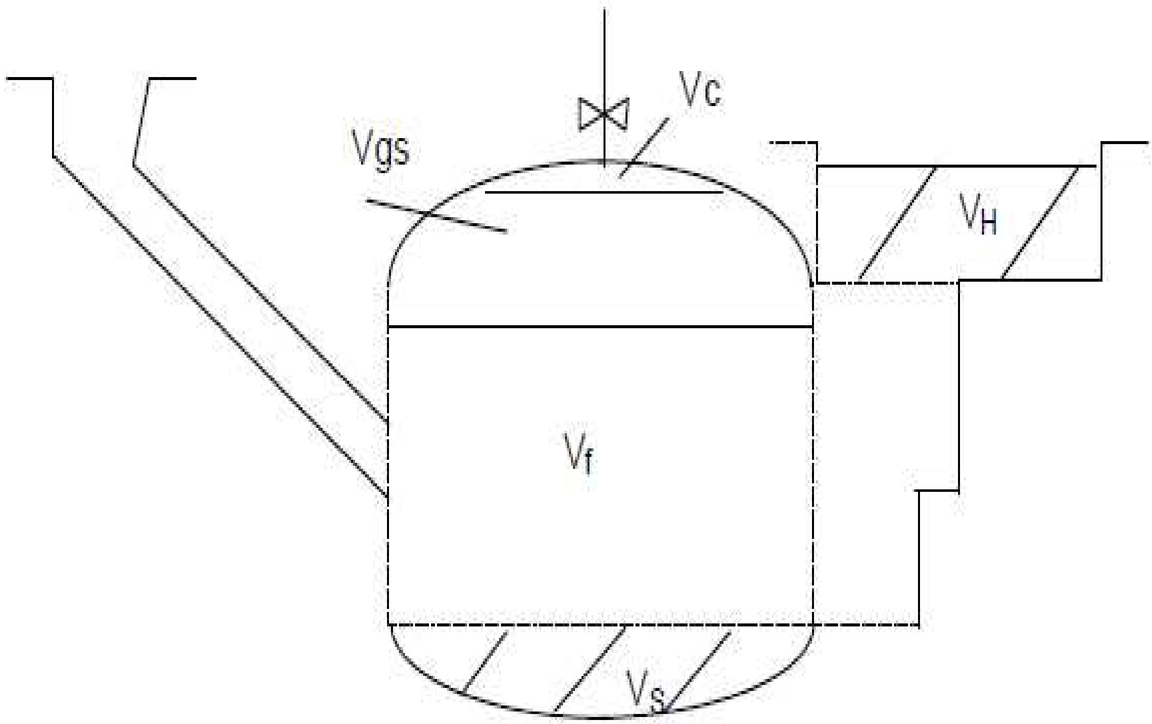

Figure 4.5: Cross-section of a digester

Where:

Volume of gas collecting chamber = V_c

Volume of gas storage chamber = V_{gs}

Volume of fermentation chamber = V_f

Volume of hydraulic chamber = V_H

Volume of sludge layer = V_s

Total volume of digester $V = V_c + V_{gs} + V_f + V_s$

Geometrical Dimensions of the Biogas Digester

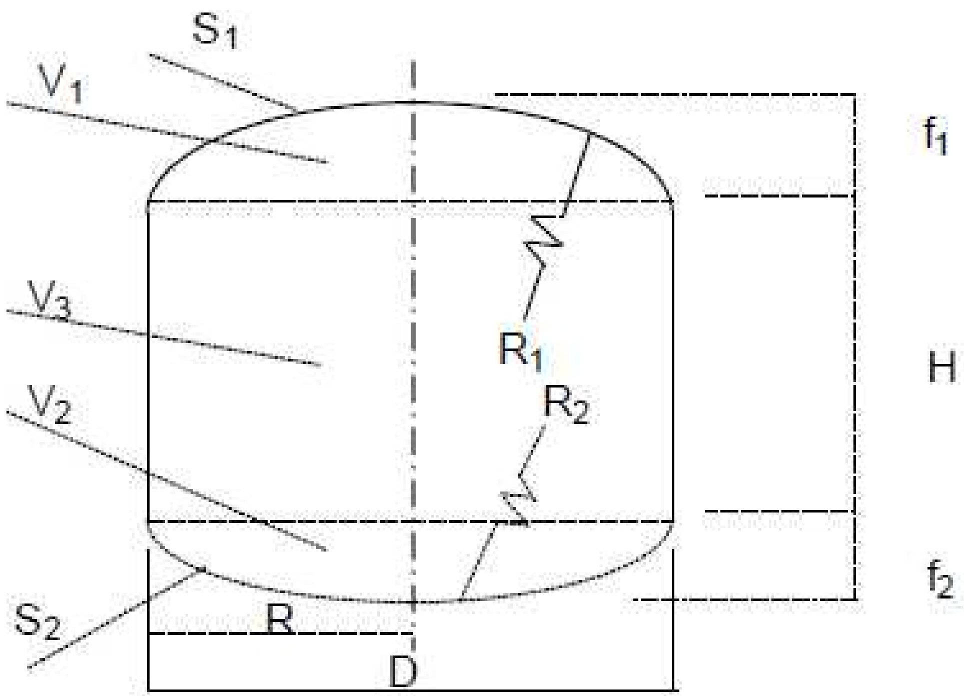

Figure 4.6: Geometrical dimensions of the biogas digester

Basic Assumptions of Biogas Digester Design:

- **Volume of the Digester** [35]

$V_c \leq 5\% V$

$V_s \leq 15\% V$

$V_{gs} + V_f = 80\% V$

$V_{gs} = V_H$

$V_{gs} = 0.5 * 0.95V * K$, Where K = 0.3, Gas production rate/m^3 digester volume per day.

- **Geometrical Dimensions of the Digester**[35]

$D = 1.3078 * V^{1/3}$

$V_1 = 0.0827 D^3$

$V_2 = 0.05011 D^3$

$V_3 = 0.3142 D^3$

$R_1 = 0.725 D$

$R_2 = 1.0625 D$

$f_1 = D/5$

$f_2 = D/8$

$S_1 = 0.911\ D^2$

$S_2 = 0.8345\ D^2$

- **Volume Calculation of Digester and Hydraulic Chamber:**

  - ✓ **Volume Calculation of Digester Chamber:** [35]

Let RT = 27 days, where RT= Retention Time

Daily Input = 505 Kg

TS of fresh input = 505 Kg * 0.3033 = 153.1665 Kg.

In 9% concentration of TS (to create a favorable condition to AD of the food waste)

Total influent required = Q

$$Q = \frac{153.1665\ \text{Kg}}{9\%}$$

$$= 1701.85\text{Kg}$$

Water to be added to make the discharge 9% concentration of TS

$$= 1701.85\text{Kg} - 505\ \text{kg}$$

$$= 1196.85\ \text{Kg}$$

Using another formula

$$\text{Water to be added} = \frac{(30.33\% - 9\%)}{9\%} * \text{Sample before water}$$

$$= \frac{(30.33\% - 9\%)}{9\%} * 505\ \text{kg}$$

$$= 1196.85\ \text{Kg}$$

Working volume of digester = $V_{gs} + V_f$

$$V_{gs} + V_f = Q * RT$$

$$= 1701.85\text{Kg/day} * 27\ \text{days}$$

$$= 45949.95\ \text{Kg}$$

$$= 45.95\ m^3$$

From Geometrical Assumptions:

$$V_{gs} + V_f = 0.8V$$

$$V = \frac{45.95\ m^3}{0.80}$$

$= 57.44\ m^3$

$D = 1.3078 * V^{1/3}$

$= 1.3078 * (57.44)^{1/3}$

$= 5m$

$V_3 = \frac{\pi D^2 H}{4}$, where $V_3 = 0.3142\ D^3$

$H = \frac{4 * 0.3142\ D^3}{3.14 * D^2}$

$= 2m$

Taking the values of H and D to the assumptions we will get:

$R_1 = 0.725\ D$

$= 0.725 * 5m$

$= 3.625m$

$R_2 = 1.0625\ D$

$= 1.0625 * 5m$

$= 5.3125m$

$f_1 = D/5 = 5m/5 = 1m$

$f_2 = D/8 = 5m/8 = 0.625m$

$V_1 = 0.0827\ D^3 = 0.0827 * (5)^3 = 10.34m^3$

$V_c = 0.05\ V = 0.05 * 57.44\ m^3 = 2.872\ m^3$

$V_2 = 0.05011\ D^3$

$= 0.05011 * (5)^3$

$= 6.264m^3$

$V_3 = 0.3142\ D^3$

$= 0.3142 * (5)^3$

$= 39.275m^3$

$V_s = 0.15V$

$= 0.15*(57.44)$

$= 8.\ 616m^3$

$S_1 = 0.911\ D^2 = 0.911 * (5)^2 = 22.775m^2$

$S_2 = 0.8345\ D^2 = 0.8345 * (5)^2 = 17.41\ m^2$

✓ **Calculation on Volume of Hydraulic Chamber:**

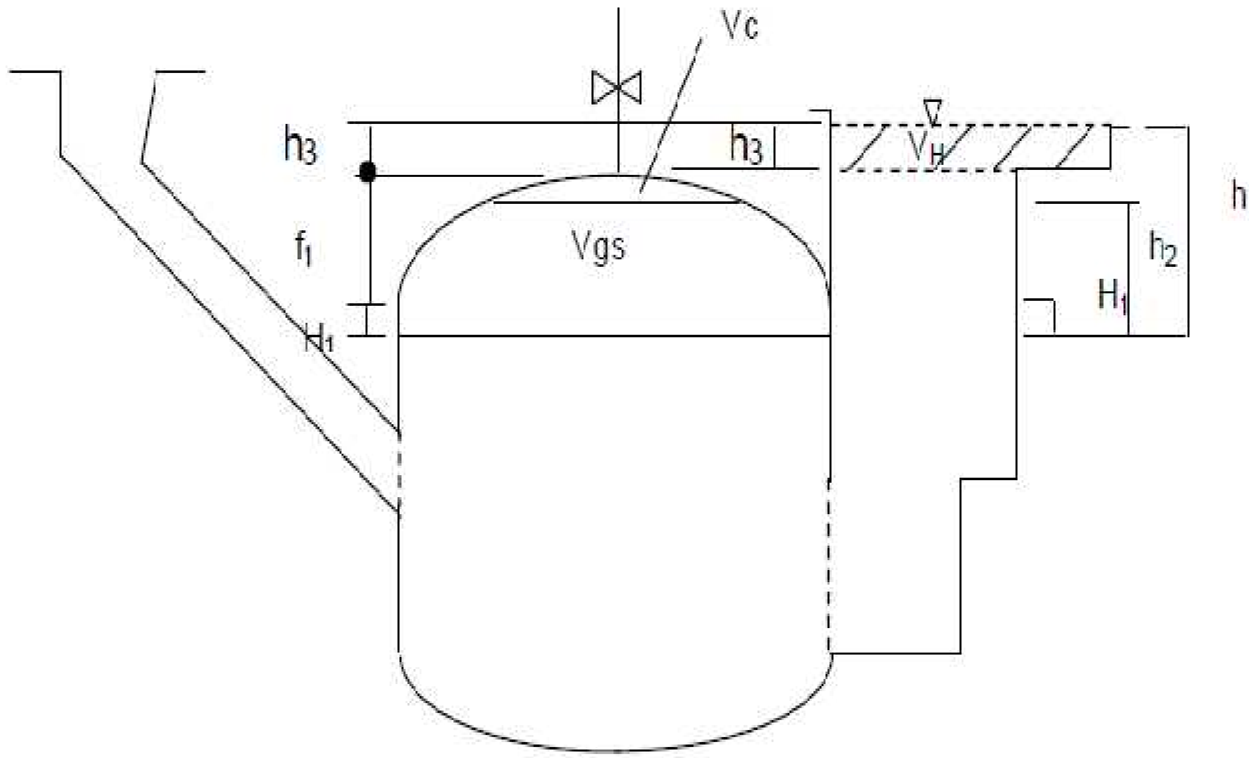

Figure 4.7: Geometrical dimensions of hydraulic chamber

$V_{gs} = 0.5 * (0.8V + V_s) * K$, where $K_r = 0.3$ = gas production rate per m^3 digested vol/day [35]

$V_{gs} = 0.5 * (0.95V) * 0.3$

$= 8.1852 m^3$

$V_{gs} + V_f = 0.8V$

$V_f = 0.8V - V_{gs}$

$= (0.8 * 57.44) - 8.1852$

$= 37.77 m^3$

$V_1 = \left[(V_c + V_{gs}) - \frac{\pi D^2 H_1}{4}\right]$, where $V_1 = 10.34 m^3$ and $D = 5m$

$H_1 = \frac{4 * [(V_c + V_{gs}) - V_1]}{\pi D^2}$

$= \frac{4 * [(2.872 + 8.1852) - 10.34]}{3.14 * (5)^2}$

$= 0.0365m$

$h = 0.8 H = 0.8 * 2 = 1.6m$

$h = h_3 + f_1 + H_1$

$h_3 = h - (f_1 + H_1)$

$h_3 = 0.564m$

$V_{gs} = V_H$

$V_{gs} = 3.14 \times (D_H)^2 * (h_3/4)$, where $V_{gs} = 8.1852m^3$

$$(D_H)^2 = \frac{V_{gs}}{[3.14 \times (D_H)^2 * (h_3/4)]}$$

$D_H = 4.3m$

4.3 Total Biogas Produced

The total biogas produced from food waste is calculated as follows:

Total biogas produced = Daily input of the food waste * biogas production rate

= 505 Kg/day * 0.04m^3/Kg

= 20.2m^3/day

Total biogas produced per hour = 20.2 m^3/day * (1/24) days/hour

= 0.84167m^3/hour

Total biogas produced per year = 20.2 m^3/day * 365 days/year

= 7373m^3/year

5.0 Conclusion and Recommendations

5.1 Conclusion

Biogas plants convert food wastes to biogas and the biogas is a clean renewable energy which will be used in different forms of environmentally friendly energy sources. The study will help Ethiopian Airlines to get an environmentally friendly energy sources by converting the 505 Kg/day food waste to biogas. From the 505 Kg/day food waste Ethiopian Airlines will get a total of $20.2m^3$/day biogas.

Three experimental analyses were done in this thesis and from the three the third experimental analysis was successful because it considers all the anaerobic biogas production parameters like pH, TS, VS, C/N ratio, temperature and others physical conditions.

There are repeated bird strikes that occurred on the aircraft bodies and engines; this is caused because birds gather around the airside looking for food. The number of bird strikes will significantly minimize by producing biogas from food waste and this production of biogas will reduce cost of gas which is used for cooking stoves and ovens.

The thesis eases identifying of the size of the biogas digester without consuming your valuable time on calculating different parameters of the biogas. Having the daily input of food waste, retention time and concentration of TS, we can easily calculate the biogas produced and size of the digester. The thesis provides a basic model that does not require many inputs or a large amount of computation time to predict biogas production over retention time.

This model can also help to determine the ideal digester sizing and feed rate for anaerobic digester. This model predicts that the rate of gas production slows over time, and a user may identify a minimum gas production rate that is profitable or otherwise utilize the ability to determine the percentage of completion of the reaction at any time.

If the ultimate analysis of the feedstock that includes mass ratios of carbon, hydrogen, oxygen, nitrogen and sulfur is inputted to the system, the model could be applied to any number of feedstock. This Matlab modeling is designed in a simple and user friendly way so that anyone can enter basic design parameters like the daily input food waste, retention time and concentration of total solid and then the model provides baseline predictions that can aid basic digester design.

5.2 Recommendations

There are many ways in which the present research could be continued. Here some topics are presented that would be of interest to investigate in the near future.

- Upgrading the biogas produced to get better and more refined methane. The upgraded biogas could be used to run an aircraft engine.
- Inclusion of ashes in ultimate analysis can lead to a calculation of accumulation of ashes. This can tell a user how much of their digester capacity they are losing over time, which could inform how regularly the digester needs to be cleaned.

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36. Ethiopian Airlines Food Service

Appendices

1. Matlab Simulation used for kinetics modeling

```
% kinetics modeling of Biogas plant
%% Sizing of Biogas
prompt = 'Insert Daily input in Kg? ';
Dailyinput = input(prompt);
prompt = 'Insert Retention Time_No of days? ';
RT = input(prompt);
prompt = 'Insert Concentration_of_TS? ';
Concentration_of_TS = input(prompt);
dwater= 1000.00;
dwaste = 1120.00;
TS= (Dailyinput)*0.3033;
water_required = (TS/Concentration_of_TS)-(Dailyinput);
Total_influent_required = (TS/Concentration_of_TS);
Total_volume_of_digester = (Total_influent_required*RT)/(0.8);
V= Total_volume_of_digester;
D= 1.3078*V^(1/3);
Hd=(4*0.3142*D^3)/(3.14*D^2);
f1= D/5;
f2= D/8;
R1= 0.725*D;
R2= 1.0625*D;
V1= 0.0827*D^3;
V2 = 0.05011*D^3;
V3 = 0.3142*D^3;
Vc= 0.05*V;
S1 = 0.911*D^2;
S2 = 0.8345*D^2;
```

```
TS=(Dailyinput)*0.3033;
Vgs= 0.5*TS*Dailyinput*0.158;
H1=4*((Vc+Vgs)-V1)/(3.14*D^2);
h3=(f1+H1)*0.2;
h=h3+f1+H1;
Vh=Vgs;
%% Kinetic Model
% kinetic coefficient
k = 2.7*10^-6 ;
% mass flow rate in (kg/day)
dAdtin = 0 ;
% masss flow rate out
dAdtout = 0 ;
% these are molar masses of each element
mm_carbon = 12.0107 ;
mm_hydrogen = 1.0079 ;
mm_oxygen = 15.999 ;
mm_nitrogen = 14.0067 ;
mm_sulphur = 32.065;
% For C_n H_a O_b N_c S_d + H20 -- CO2 + CH4 + H2S+ NH3
% These constants come from the ultimate analysis
% These constants dictate the coefficients of each term
nbymass = 0.45405 ;
abymass = 0.07655 ;
bbymass = 0.42915 ;
cbymass = 0.03945 ;
dbymass = 0.004 ;
% to get molar ratios we divide by molar mass
n = nbymass/mm_carbon;
a = abymass/mm_hydrogen;
b = bbymass/mm_oxygen;
```

```
c= cbymass/mm_nitrogen;
d= dbymass/mm_sulphur;
% These are the coefficients in front of each component of the reaction.
% C_n H_a O_b N_c S_d + c_1*H20 -- c_2*CO2 + c_3*CH4+c_4*NH3 + c_5*H2S
c_1 = n - a/4 -b/2+(3/4)*c+d/2;
c_2 = n/2 -a/8 + b/4+(3/8)*c+d/4;
c_3 = n/2 + a/8 - b/4-(3/8)*c-d/4;
c_4 = c;
c_5 = d;
% These are the molar masses of each component
mm_A = mm_carbon*n + mm_hydrogen*a + mm_oxygen*b+ mm_nitrogen*c+ mm_sulphur*d;
mm_B = 2*mm_hydrogen + mm_oxygen ;
mm_C = mm_carbon + 2*mm_oxygen ;
mm_D = mm_carbon + 4*mm_hydrogen ;
mm_E = mm_nitrogen + 3*mm_hydrogen;
mm_F = 2*mm_hydrogen+mm_sulphur;
% These are the masses of each component per mol of food waste
m_A = mm_A;
m_B = c_1*mm_B;
m_C = c_2*mm_C;
m_D = c_3*mm_D;
m_E = c_4*mm_E;
m_F = c_5*mm_F;
ratio = m_C/(m_C + m_D + m_E + m_F);
% Initial conditions, mass in Kg, digester capacity in m3, volume of reaction in m3
mass_of_FoodWaste = Dailyinput;
mass_of_water = water_required;
density_of_FoodWaste = 1120;
density_of_water = 1000;
volume_of_reaction = (mass_of_FoodWaste/density_of_FoodWaste +
mass_of_water/density_of_water);
```

```
digester_capacity=(Total_influent_required*RT)/(0.8);
Ahat_0 = mass_of_FoodWaste/mm_A/digester_capacity ;
Bhat_0 = mass_of_water/mm_B/digester_capacity ;
Chat_0 = 0;
Dhat_0 = 0;
Ehat_0 = 0;
Fhat_0 = 0;
dAhatdt_0 = -k*Ahat_0*(Bhat_0^(c_1)) ;
dBhatdt_0 = -k*Ahat_0*(Bhat_0^(c_1))*c_1 ;
dChatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_2 ;
dDhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_3 ;
dEhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_4 ;
dFhatdt_0 = k*Ahat_0*(Bhat_0^(c_1))*c_5 ;
%% Can iterate this process for very small steps of time to approximate the
% new concentration of each component of the reaction
% Concentration of each component put into a row vector
tfinal = RT*24*60*60 ;    % retention time : RT
t = (1:tfinal) ;
Ahat = zeros(1,tfinal) ;
Bhat = zeros(1,tfinal) ;
Chat = zeros(1,tfinal) ;
Dhat = zeros(1,tfinal) ;
Ehat = zeros(1,tfinal) ;
Fhat = zeros(1,tfinal) ;
% Rate of concentration of each component put into a row vector
dAhatdt = zeros(1,tfinal) ;
dBhatdt = zeros(1,tfinal) ;
dChatdt = zeros(1,tfinal) ;
dDhatdt = zeros(1,tfinal) ;
dEhatdt = zeros(1,tfinal) ;
dFhatdt = zeros(1,tfinal) ;
```

```
% initial conditions put into the first index of the vectors
Ahat(1) = Ahat_0 ;
Bhat(1) = Bhat_0 ;
Chat(1) = Chat_0 ;
Dhat(1) = Dhat_0 ;
Ehat(1) = Ehat_0 ;
Fhat(1) = Fhat_0 ;
dAhatdt(1) = dAhatdt_0 ;
dBhatdt(1) = dBhatdt_0 ;
dChatdt(1) = dChatdt_0 ;
dDhatdt(1) = dDhatdt_0 ;
dEhatdt(1) = dEhatdt_0 ;
dFhatdt(1) = dFhatdt_0 ;
% simulation run for small time steps to give concentration over time
for i = 2:tfinal
Ahat(i) = Ahat(i-1) + dAhatdt(i-1) ;
Bhat(i) = Bhat(i-1) + dBhatdt(i-1) ;
Chat(i) = Chat(i-1) + dChatdt(i-1) ;
Dhat(i) = Dhat(i-1) + dDhatdt(i-1) ;
Ehat(i) = Ehat(i-1) + dEhatdt(i-1) ;
Fhat(i) = Fhat(i-1) + dFhatdt(i-1) ;
dAhatdt(i) = -k*Ahat(i)*(Bhat(i)^(c_1)) ;
dBhatdt(i) = -k*Ahat(i)*(Bhat(i)^(c_1))*c_1 ;
dChatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_2 ;
dDhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_3 ;
dEhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_4 ;
dFhatdt(i) = k*Ahat(i)*(Bhat(i)^(c_1))*c_5 ;
end
% mols converted to mass of gas produced
mols_of_c = Chat*digester_capacity ;
mols_of_d = Dhat*digester_capacity ;
```

```
mols_of_e = Ehat*digester_capacity ;
mols_of_f = Fhat*digester_capacity ;
mass_of_CO2 = mols_of_c*mm_C ;
mass_of_CH4 = mols_of_d*mm_D ;
mass_of_NH3 = mols_of_e*mm_E ;
mass_of_H2S = mols_of_f*mm_F ;
% fitting factor used to adjust model to experiment
fitting_factor = .0085 ;
mass_of_CO2_fitted = mass_of_CO2*fitting_factor ;
mass_of_CH4_fitted = mass_of_CH4*fitting_factor ;
mass_of_NH3_fitted = mass_of_NH3*fitting_factor ;
mass_of_H2S_fitted = mass_of_H2S*fitting_factor ;
t_fitted = t/(60*60*24) ;
pressure_Pa = 101325 ;
T = 311 ; %K ;
R = 8.314 ; %J/mol/K
Volume_of_CO2 = (mass_of_CO2_fitted*R*T)/(pressure_Pa*mm_C)*10000;
Volume_of_CH4 = (mass_of_CH4_fitted*R*T)/(pressure_Pa*mm_D)*10000;
Volume_of_NH3 = (mass_of_NH3_fitted*R*T)/(pressure_Pa*mm_E)*10000;
Volume_of_H2S = (mass_of_H2S_fitted*R*T)/(pressure_Pa*mm_F)*10000;
Vol_Biogas =
(0.32*Volume_of_CO2+0.65*Volume_of_CH4+0.1*Volume_of_NH3+0.2*Volume_of_H2S);
plot(t_fitted, Volume_of_CH4,'b', t_fitted, Volume_of_CO2, 'r',t_fitted,Volume_of_NH3,'g',
t_fitted, Volume_of_H2S,'b', t_fitted,Vol_Biogas,'c','LineWidth',1.6)
legend('CH4 model', 'CO2 model', 'NH3 model', 'H2S model', 'Biogas Model')
set(gca,'FontSize',12,'FontWeight','bold','linewidth',1.5)
ylabel('Gas produced (m^3)','FontSize',12,'FontWeight', 'bold')
xlabel('Retention time(days)','FontSize',12,'FontWeight', 'bold')
XLIM([0 27])
```

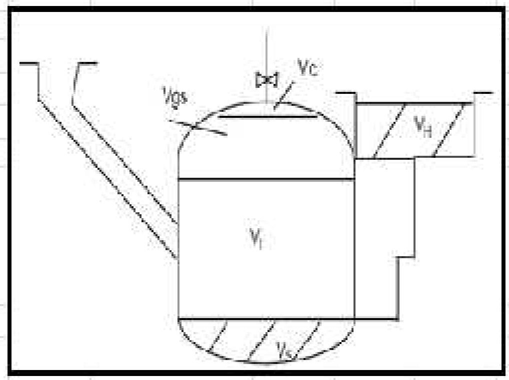
2. Matlab Simulation of Biogas Digester Sizing

```
% This code helps to size and give dimensions to Biogas plant
%% Sizing of Biogas Digester
prompt = 'Insert Daily input in Kg? ';
Dailyinput = input(prompt);
prompt = 'Insert Retention Time_No of days? ';
RT = input(prompt);
prompt = 'Insert Concentration_of_TS? ';
Concentration_of_TS = input(prompt);
dwater= 1000.00;
dwaste = 1120.00;
TS=(Dailyinput)*0.3033;
water_required = (TS/Concentration_of_TS)-(Dailyinput);
Total_influent_required = (TS/Concentration_of_TS);
Total_volume_of_digester =(Total_influent_required*RT*10^-3)/(0.8);
V= Total_volume_of_digester;
Vc=0.05*V;
Volume_of_gas_collecting_chamber= Vc;
Gas_produced=0.04*Dailyinput;
Gas_storage_volume =0.6*Gas_produced;
Vs=0.15*V;
Vgs=0.1425*V;
Volume_of_gas_storage_chamber =Vgs;
Vf=(0.8*V)-Vgs;
D = 1.3078*(V^(1/3));
H=(4*0.3142*D^3)/(3.14*D^2);
f1= D/5;
f2= D/8;
R1= 0.725*D;
R2= 1.0625*D;
V1= 0.0827*D^3;
```

```
V2 = 0.05011*D^3;
V3 = 0.3142*D^3;
Vc= 0.05*V;
S1 = 0.911*D^2;
S2 = 0.8345*D^2;
H1=4*((Vc + Vgs)-V1)/(3.14*D^2);
h=0.8*H;
h3=h-f1-H1;
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Dailyinput,1,'C3')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',RT,1,'C4')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Concentration_of_TS,1,'C5')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',D,1,'C6')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',H,1,'C7')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',f1,1,'C8')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',f2,1,'C9')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',R1,1,'C10')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',R2,1,'C11')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',S1,1,'C12')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',S2,1,'C13')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',V,1,'C14')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Vc,1,'C15')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Vgs,1,'C16')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Vf,1,'C17')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Vs,1,'C18')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',H1,1,'C19')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',h3,1,'C20')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',h,1,'C21')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',Gas_produced,1,'C24')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',V1,1,'G3')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',V2,1,'G4')
xlswrite('C:\BiogasDesign\Sizing Data.xlsx',V3,1,'G5')
```

Biogas Digester Sizing		
Daily input	505	Kg
Retention time	27	Days
Concentration of TS	[illegible]	-
D	5.046	m
H	2.020	m
f1	1.009	m
f2	0.631	m
R1	3.658	m
R2	5.351	m
S1	23.195	m^2
S2	21.247	m^2
V	57.437	m^3
Vc	2.872	m^3
Vgs	8.185	m^3
Vf	37.765	m^3
Vs	8.616	m^3
H1	0.022	m
hs	0.585	m
h	1.616	m
VH	8.185	m^3
Gas holder sizing		
Gas Produced	20.2	m^3 biogas/day

Final Dimension		
V1	10.525	m^3
V2	5.438	m^3
V3	40.367	m^3
D	5.046	m
R1	3.658	m
R2	5.361	m
f1	1.009	m
H	2.020	m
f2	0.631	m



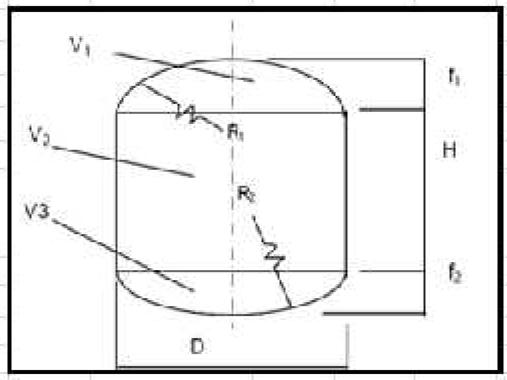
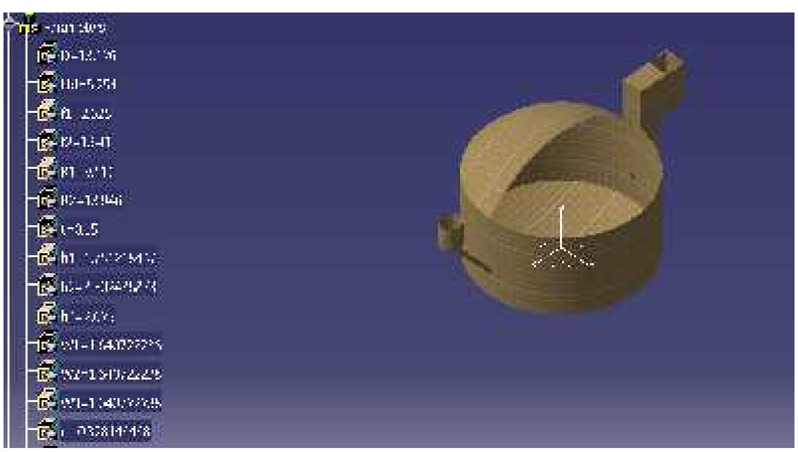


Figure A.1: Biogas Digester Sizing



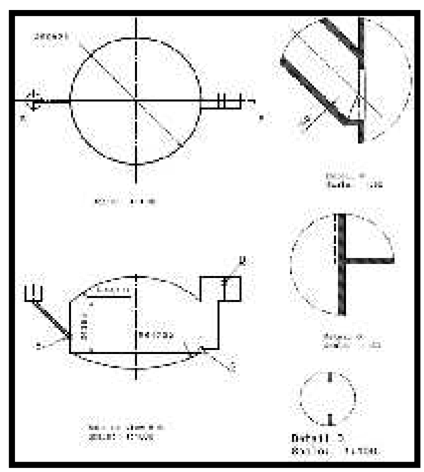


Figure A.2: Integration result of Matlab, Excel and Catia to size, dimension and plot Biogas in 3D and 2D – Sectional view of Biogas plant

Note : This integration of Matlab, Excel and Catia is an innovative approach that can help to size any Biogas plant, plot in 3D. Thus, by using the 2D dimensional information, the Biogas plant can be constructed.

Instruments used during the experimental analysis

pH Meter

Weighing Scale

Gas Analyzer

Water Bass

Air Bag

Vacuum Pump

Furnace

Oven

Figure A.2: Instruments Used

3. Ethiopian Airlines Food Waste Collected Data

4.1 FW data collected on 14-Mar-2016

FW from Main Cafeteria

Item No	Food Type	Weight (Kg)	Percentage
1	Enjera with Wot	128	52%
2	Vegetable	44	18%
3	Pasta and macaroni	24	10%
4	Rice	40	16%
5	Bread	10	4%
	Total	246	

FW from Inflight Catering

Item No	Food Type	Weight (Kg)	Percentage
1	Rice	100	35%
2	Vegetable	58	20%
3	Beef, Fish and Chicken	77	27%
4	Enjera with Wot	52	18%
	Total	287	

4.2 FW data collected on 15-Mar-2016

FW from Main Cafeteria

Item No	Food Type	Weight (Kg)	Percentage
1	Enjera with Wot	147	48%
2	Vegetable	77	25%
3	Pasta and Macaroni	36	12%
	Rice	28	9%
4	Bread	18	6%
	Total	306	

FW from Inflight Catering

Item No	Food Type	Weight (Kg)	Percentage
1	Rice	92	40%
2	Vegetable	46	20%
3	Beef, Fish and Chicken	39	17%
4	Enjera with Wot	53	23%
	Total	230	

4.3 FW data collected on 16-Mar-2016

FW from Main Cafeteria

Item No	Food Type	Weight (Kg)	Percentage
1	Enjera with Wot	88	41%
2	Vegetable	42	20%
3	Pasta and Macaroni	28	13%
	Rice	38	17%
4	Bread	21	9%
	Total	217	

FW from Inflight Catering

Item No	Food Type	Weight (Kg)	Percentage
1	Rice	92	30%
2	Vegetable	62	20%
3	Beef, Fish and Chicken	87	28%
4	Enjera with Wot	68	22%
	Total	309	

3.4 FW data collected on 17-Mar-2016

FW from Main Cafeteria

Item No	Food Type	Weight (Kg)	Percentage
1	Enjera with Wot	139	53%
2	Vegetable	45	17%
3	Pasta and macaroni	25	9%
	Rice	28	11%
4	Bread	26	10%
	Total	263	

FW from Inflight Catering

Item No	Food Type	Weight (Kg)	Percentage
1	Rice	72	28%
2	Vegetable	48	19%
3	Beef, Fish and Chicken	59	23%
4	Enjera with Wot	76	30%
	Total	255	

3.5 FW data collected on 18-Mar-2016

FW from Main Cafeteria

Item No	Food Type	Weight (Kg)	Percentage
1	Enjera with Wot	130	63%
2	Vegetable	17	8%
3	Pasta and Macaroni	30	14%
	Rice	24	12%
4	Bread	6	3%
	Total	207	

FW from Inflight Catering

Item No	Food Type	Weight (Kg)	Percentage
1	Rice	80	30%
2	Vegetable	48	18%
3	Beef, Fish and Chicken	96	36%
4	Enjera with Wot	42	16%
	Total	266	