ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)
SCHOOL OF CHEMICAL AND BIOENGINEERING
ENVIRONMENTAL ENGINEERING POST GRADUATE PROGRAM

M.Sc. Thesis on:

Comparative Study on Biogas Production Potential of Sewage, Slaughterhouse, Fruit-Vegetable Wastes and their Co-digestion

A Thesis Submitted in Partial Fulfillment of the Requirements for the Award of a Master's Degree in Chemical Engineering under Environmental Engineering stream.

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May God bless all of you!

Alemu Gizaw Wakene

July, 2016

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Acronym and Symbols

BOD_5	Biochemical oxygen demand
CHP	Combined Heat and Power
C: N	Carbon to nitrogen
COD	Chemical oxygen demand
FVW	Fruit-Vegetable Waste
gVS	gram volatile solids
HRT	Hydraulic Retention Time
LCFA	Long-chain Fatty Acid
M	Mixture
N	Normality
OFMSW	Organic fraction of municipal solid waste
SHW	Slaughterhouse Waste
SW	Sewage Waste
TS	Total solid
v/v	Volume by volume
VFA	Volatile fatty acid
VS	Volatile solid
VS_f	Volatile solids of digestate
VS_i	Volatile solids of feed
W_{DC}	Weight of dry crucible in gram
W_{DS}	Weight of dry sample at 103°C
W_{VS}	Weight of volatile solids
W_{WS}	Weight of wet sample in gram

Abstract

Currently, 1.5 liters per person per day (De Mes and Stams, 2003) faeces and urine as sewage waste, 45 to 60m^3/day SHW and 2 to 3 trucks/day of FVW generated in Addis Ababa. The main objective of this work was to make comparative study on the biogas generation potential of SW, SHW, FVW, and their co-digestion (M) by using wet batch anaerobic digestion technology. Specifically the study investigated how the performance of anaerobic digestion is affected by temperature, retention time, and waste types. The temperature levels used were room temperature, 37°C and 45°C. Wet mesophilic anaerobic digestions of SW, SHW, FVW and co-digestion of their mixture have been investigated. Wastes samples were characterized in terms of TS, VS, pH, BOD_5, COD, total nitrogen and C: N ratio as per the existing standards. Biogas produced was characterized using biogas analyzer. The data from the experiment was analyzed and modeled using Design-Expert version 6.0.8 and significance was accepted at 0.05 level of probability ($p<0.05$). Comparatively, maximum of 63.9, 77.8, 70.0 %CH_4 biogas was observed for co-digestion of aforementioned wastes at room, 37°C and 45°C, respectively. This study shows that %CH_4 in the biogas increases with retention time until it reaches optimum point and decrease afterwards. It also shows that biogas production increases in the temperature range investigated irrespective of waste types. Maximum methane yields of 0.12 and 0.16 liters per gram volatile solids digestion (lCH_4/gVS) was achieved at 37°C from SHW and M, respectively. Similarly, maximum methane yields of 0.09 and 0.13 lCH_4/gVS was achieved at 45°C from FVW and SWs, respectively.

Keywords: Sewage waste, Co-digestion, Fruit-Vegetable waste, Methane yield

1. INTRODUCTION

1.1. Background

Historical evidence indicates that the anaerobic digestion process is one of the oldest technologies. The industrialization of anaerobic digestion began in 1859 with the first digestion plant in Bombay, India. Anaerobic digestion has been exploited to produce biogas and fertilizer for hundreds, perhaps thousands of years by the Chinese, Assyrians and Persians (Fabien, 2003). In developed countries, significant potential for biogas use exists. By 1895, biogas was recovered from a sewage treatment facility and used to fuel street lambs in Exeter, England (Fabien, 2003). In the 1930's anaerobic bacteria and the conditions that promote methane production were identified (Fabien, 2003). In Sweden, a biogas powered train has been in service since 2005. In the United Kingdom, biogas is estimated to have the potential to replace about 17% of vehicle fuel (Adelekan and Bamgboye, 2009).

Subsequent to the oil crisis in the 1970's and the high oil prices in recent years, the interest in renewable energy such as biogas increased in most parts of the world. Biogas technology was introduced in Ethiopia as early as 1979, when the first batch type digester was constructed at the Ambo Agricultural College. In the last three decades around 1000 biogas plants, ranging in size from $2.5m^3$ to $200m^3$, were constructed in households, community and governmental institutions in various parts of the country (National Biogas Programme Ethiopia, 2008). Presently, some of the biogas plants that were constructed are not operational due to a lack of effective management and follow-up, technical problems, loss of interest, reduced animal holdings, evacuation of ownership, water problems, etc (National Biogas Programme Ethiopia, 2008).

Ethiopia has no access to advanced fuels such as petroleum and natural gas. Almost all fuel consumption of the rural area of the country is obtained mainly from the traditional biomass (Dawit, 2008).

Traditional energy use increases the rate of deforestation and land degradation, which in turn can lead to excess soil erosion and loss of soil fertility. This further contributes to the decline of agricultural productivity and production, perpetuating the vicious cycle of rural poverty. Indoor air pollution associated with kerosene and traditional fuel use is a major health concern, especially for women and children (Sustainable Energy for All, 2015). Reliance on traditional energy sources of biomass brought threat from overuse, creating additional environmental

challenges ranging from local land use to global climate change and applications in smoky kitchens. If current fuel wood utilization trends continue, most developing countries are predicted to experience severe shortage of fuel wood by 2025. In sum, it leads to depletion of tree stocks or threat to biodiversity, desertification, reduced water quality, sedimentation, dust storms, air pollution and health problems such as respiratory illnesses and allergies (Dagninet, et al., 2015).

Anaerobic digestion is a natural process, commercially proven and widely used technology option consistent with cleaner production and sustainable development due to the positive energy balance in the waste treatment; lowered production of sludge waste and the fact that the sludge thus produced has a higher degree of stabilization (Iván and Liliana, 2010). This process can produce energy in the form of biogas, and safe stable bio-fertilizer in the form of digestate (Iván and Liliana, 2010; Satoto, 2010).

Biogas is a renewable source of energy. Biogas is a mixture of gases comprising 50 to 75% methane (CH_4), 25 to 45% carbon dioxide (CO_2) and 0 to 5% a combination of hydrogen sulfide (H_2S), N_2, H_2 and others (Florian, 2013). The carbon dioxide that is released when biogas is combusted and mixed with the oxygen in the air does not contribute to the greenhouse effect as the carbon in the methane molecule originates from carbon dioxide in the air that growing plants have previously taken up by photosynthesis. As a result, the use of biogas is thus an important step in climate change mitigation. The development of biogas represents a strategically important step away from oil dependency that will contribute to a sustainable energy supply in the long term. Biogas is also produced locally meaning that it is not dependent on trade relationships. This also contributes to improved energy security (Lars, 2012)

Eventhough, anaerobic digestion technology has more than a century historical background scientific interest and efforts in researching biogas production technology are still relevant because of the often very high costs of energy supply worldwide. Another rationale for their relevance is the fact that the rampant use of firewood for domestic cooking in low income countries invariably results in the destruction of forests which is harmful to the environment (Adelekan and Bamgboye, 2009).

1.2. Statement of the problem

Ethiopia is one of the developing countries with more than 90 million populations. In fact waste generation rate increases with population number and developmental activities in the country. As population number increases, waste management and provision of sustainable energy for economic development become challenging. To overcome this challenge and contribute to sustainable development, utilizing energy from wastes using appropriate technology is one of the recommended options. In other hand, an increase in waste generation rate is an opportunity to produce biogas energy using appropriate technology. As currently observed in Addis Ababa, 2 to 3 trucks fruit-vegetable wastes from fruit -vegetable wholesale market of Piassa is dumped at Raphi or Koshe site daily. According to De Mes and Stams (2003) report, 1.5 liters per person per day faeces and urine generated as sewage waste from condominium sites in Addis Ababa. Moreover, 45 to 60m^3/day slaughterhouse waste from Addis Ababa Abattoir Enterprise is also directly discharged to nearby water bodies without appropriate treatment. Merely disposal of these wastes results in bad odor, water streams eutrophication, loss of clean water and different health problems on the nearby communities. Treatment of sewage, slaughterhouse and fruit-vegetable wastes in Addis Ababa using anaerobic digestion, which is a promising technology and potential environment-friendly technique to recover energy in the form of biogas and bio-fertilizer in the form of digestate from these wastes.

1.3. Objectives

1.3.1. General objective

The main objective of this work was to make comparative study on the biogas generation potential of condominium sewage, slaughterhouse, fruit- vegetable wastes, and their co-digestion.

1.3.2. Specific objectives

The specific objectives are to:

- Characterize the waste mixtures in terms of C: N, pH, BOD_5, COD, TS, and VS.
- Determine appropriate mixture ratio
- Studying effect of parameters affecting the performance of anaerobic digester.
- To characterize the biogas product.

1.4. Significance of the study

Using sewage, slaughterhouse wastes and fruit-vegetable wastes for biogas production has versatile advantages. It provides option to exploited biogas energy from this sector. Together with electricity from hydropower, biogas energy can replaces traditional fuels such as charcoal, wood, sawdust, and dung make for cooking. Digestate bio-fertilizer can replace inorganic fertilizer as it is best soil conditioner. This help to reduce poverty as it decrease financial and economic costs expended on fuel and inorganic fertilizer. Cooking with smokeless will diminish the number of eye infections and respiratory problems of women and children being near their mothers. Using sewage, slaughterhouse wastes and fruit-vegetable wastes for biogas production also help reduce land fill demand and contribute to the aesthetics and cleanliness of the city.

2. LITERATURE REVIEW

2.1. Biogas

Biogas is a flammable gas produced by microbes when organic materials are fermented in a certain range of temperatures, moisture contents, and acidities under air-tight conditions (Adelekan and Bamgboye, 2009). The chemical properties of biogas are that it is very stable, does not dissolve in water, and is lighter than air. Pure CH_4 is a colorless, tasteless, and odorless gas, but as the biogas consists of a small amount of H_2S, it smells very slightly of rotten eggs. When the CH_4 and air mixture burns, a blue flame is emitted, and it produces a large amount of heat energy (Florian, 2013). It is an energy source with a low carbon footprint (Michaela, 2010). Biogas is mainly composed of 50 to 75 %CH_4, 25 to 45 %CO_2 and low amounts of other gases as shown in the Table 2.1.

Table 2.1: Biogas Compositions (Florian, 2013)

Component	Symbol	% by volume
Methane	CH_4	50 – 75
Carbon dioxide	CO_2	25 – 45
Hydrogen	H_2	< 1
Nitrogen	N_2	< 2
Water vapor	H_2O	2 – 7
Hydrogen sulfide	H_2S	0.002 - 2
Ammonia	NH_3	< 1
Traces gases	-	< 2

Biogas is about 20% lighter than air and has an ignition temperature in the range of 650°C to 750°C (Florian, 2013). It is an odorless after burning and colorless gas that burns with clear blue flame (Jan and Felix, 2010). Calorific value of biogas is variable between 20 to 25 MJ/m^3 depending on its CH_4 content (Edison, 2014).

The heating oil equivalent is approximately 0.5 to 0.7 liters oil /m^3 biogas. Biogas is thus an excellent source of renewable energy (Frost and Gilkinson, 2011). The main physical characteristics of biogas are given in Table 2.2.

Table 2.2: Characteristics of Biogas (Buysman, 2009; Edison, 2014)

Characteristic of biogas	Value
Energy content	20 - 25 MJ/m^3
Ignition temperature	650 - 750 °C
Density	1.2 kg/m^3
Critical pressure	75 - 89 bar
Critical temperature	-82.5°C

Wet anaerobic digestion is one digestion type used specially for wastes contain low total solids. Different organic wastes such as animal manure, food waste, crop residue and like generates biogas and digestate. Biogas is normally burnt directly in a gas boiler to produce heat or burnt in a combined heat and power (CHP) unit to produce heat and electricity as shown in Figure 2.1.

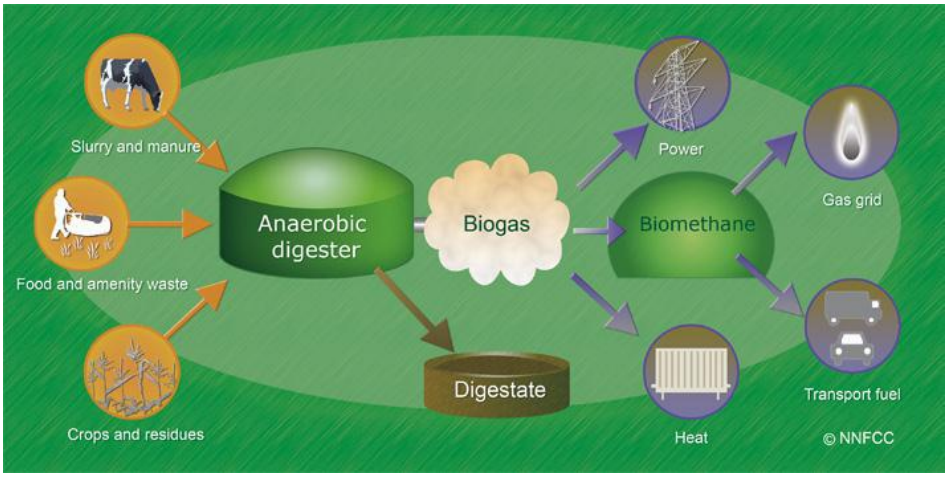


Figure 2.1: Alternative uses of biogas (Suzie, 2013, p. 3)

2.2. Anaerobic digestion process

Anaerobic digestion is a naturally occurring process where biodegradable matter is converted into biogas and a semi-solid material (digestate), by micro-organisms in the absence of oxygen (Suzie, 2013).Anaerobic digestion is a commercially proven technology and is widely used for recycling and treating animal manure, human excreta, fruit-vegetable wastes, slaughterhouse wastes and other organic wastes, which allows the production of a universal energy carrier, CH_4. It is a series of processes involving micro-organisms to break down biodegradable material successively in a multistep process and parallel reactions (Satoto, 2010).

The anaerobic digestion process of complex organic polymers is commonly divided into four inter-related steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

2.2.1. Hydrolysis

Hydrolysis is the first stage of the organic waste decomposition process involving the breakdown of large organic polymer chains into smaller molecules such as simple sugars, amino acids and fatty acids. Saccharolytic and proteolytic micro-organisms break down sugars and proteins, respectively (Edison, 2014).

Proteins, simple sugars and starch hydrolyse easily under anaerobic conditions. Normally the decomposition of organic matter to CH_4 and CO_2 is not absolute and is frequently only about 30 to 60% for animal manure and other substrates that have a high concentration of complex molecules (Peter, 2009).

Different specialized bacteria produce a number of specific enzymes that catalyse the decomposition. The process is extracellular as it takes place outside the bacterial cell in the surrounding liquid (Peter, 2009). The various enzymes that help for sugars and fats decomposition are shown in Table 2.3.

Table 2.3: Hydrolytic Enzymes and Their Functions (Edison, 2014)

Enzyme	Substrate	Break down Products
Proteinase	Protein	Amino Acids
Cellulase	Cellulose	Cellobiose and glucose
Hemicellulase	Heicellulose	Sugars e.g. glucose, xylose, mannose
Amylase	Starch	Glucose
Lipase	Fats	Fatty acids and glycerol
Pectinanse	Pectin	Sugars e.g. galactose, arabinose

The hydrolysis is often reported as rate limiting in digestion of complex polymers in balanced anaerobic digestion systems, while the methanogenesis is regarded as rate-limiting for more easily degraded substrates. Protein and carbohydrate degrading bacteria grow rapidly, and these kinds of substrates are rapidly fermented, with a retention time of less than a day (Murto, et al., 2004).

If the substrate is easily hydrolyzed, the last degradation step is often rate limiting since methanogens grow more slowly than the acidogens upstream in the degradation chain. This is due to a build-up of the metabolic intermediates, mainly volatile fatty acids (VFAs). The acid-consuming methanogenic species are more inhibited by a decrease in pH than are the acid-producing species. This causes further acid accumulation and eventually leads to process failure (Murto, et al., 2004).

2.2.2. Acidogenesis

Fermentative bacteria or acidogenic produce an acidic environment in the digestion reactor while creating hydrogen (H_2), carbon dioxide (CO_2), shorter volatile fatty acids (VFA), and organic acids like acetic, propionic, butyric, succinic, lactic acid as well as low alcohols. In a balanced bacterial process approximately 50% of the monomers like glucose, xylose, amino acids and long chain fatty acids (LCFA) are broken down to acetic acid (CH_3COOH). Further 20% is converted to CO_2 and H_2, while the remaining 30% is broken down into short chain volatile fatty acids.

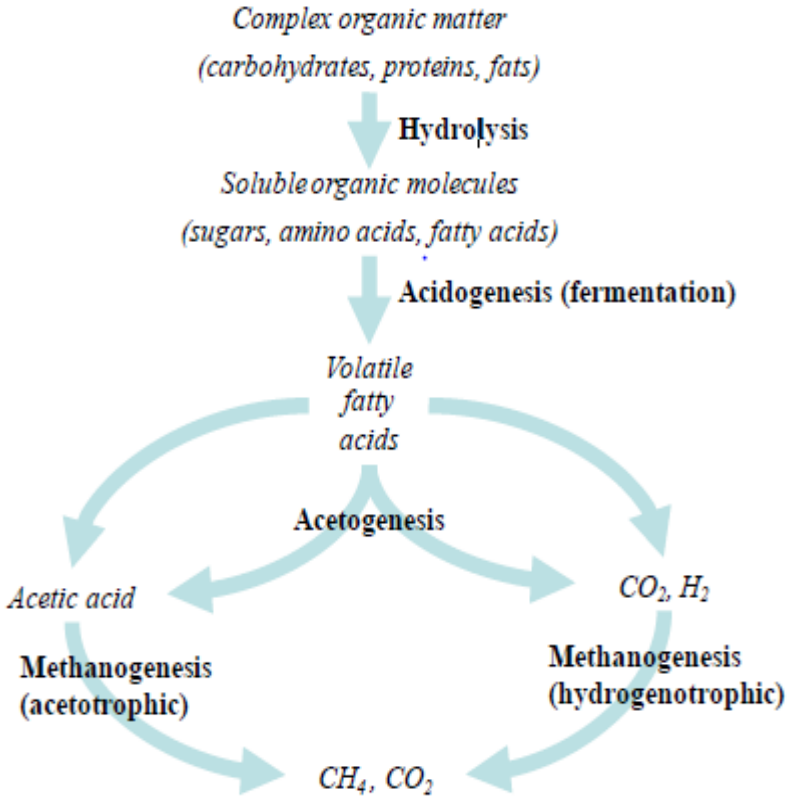


Figure 2.2: Anaerobic digestion process (California Integrated Waste Management Board, 2008)

If there is an imbalance, the relative level of VFAs will increase with the risk of accumulation and the process "turning sour" because the VFA degrading bacteria have a slow growth rate and cannot keep up. A steady degradation of VFAs is therefore crucial and often a limiting factor for the biogas process (Peter, 2009). However; these resulting organic matter is still very large and unsuitable for methane production (Edison, 2014). They need extra steps for further decomposition. Moreover, at this stage semi-harmful contaminants such as hydrogen sulfide and ammonia are produced in much smaller amounts; <1 % by volume (California Integrated Waste Management Board, 2008).

2.2.3. Acetogenesis

Volatile fatty acids and alcohols are oxidized into acetate, hydrogen and carbon dioxide before conversion into methane. This process is closely interlinked with methanogenesis (Florian, 2013).

2.2.4. Methanogenesis

The final stage of anaerobic digestion is methane production stage, where methanogens produce methane from hydrogen, carbon dioxide and acetate as well intermediates products from hydrolysis and acidogenesis by various methanogens active during this stage. Methanogens are not common bacteria but are called archaea. The dominant methanogens in the biogas process has a doubling time of up to 12 days. The low growth rate means that the methanogenesis step is restricting the input rate of organic matter. Methanogens need a pH 6.5 to 8 to remain active and are therefore particularly sensitive to pH, presence of heavy metals and organic pollutants interference in the process. Because these organisms are important also in the anaerobic oxidation, interference in the methanogenesis may have serious consequences for the entire process (Catarina, 2011; Edison, 2014).

Three biochemical pathways are used by methanogens to produce methane gas. The pathways along with the stoichiometries of the overall chemical reactions are:

Acetotrophic methanogenesis: $4\ CH_3COOH \longrightarrow 4\ CO_2 + 4\ CH_4$ (2.1)

Hydrogenotrophic methanogenesis: $CO_2 + 4\ H_2 \longrightarrow CH_4 + 2\ H_2O$ (2.2)

Methylotrophic methanogenesis: $4\ CH_3OH + 6\ H_2 \longrightarrow 3\ CH_4 + 2\ H_2O$ (2.3)

The first and second reaction above involves aceticlastic methanogenesis and reductive methanogenesis, respectively (California Integrated Waste Management Board, 2008; Satoto, 2010). Methanol is shown as the substrate for the methylotrophic pathway, although other methylated substrates can be converted. Sugars and sugar-containing polymers such as starch and cellulose yield one mole of acetate per mole of sugar degraded. Since acetotrophic methanogenesis is the primary pathway used, theoretical yield calculations are often made using this pathway alone (California Integrated Waste Management Board, 2008; Edison, 2014). According to the solid content of the material digested and the temperature at which the process operates, the various biogasification processes can be classified as under:

a. Wet anaerobic digestion:

Wet digestion means a process where the substrate contains less than 12% TS and is possible to pump (Catarina, 2011). Wet anaerobic digestion is suitable for treatment of wastes with low solid concentration such as sewage waste, industrial wastewaters, slaughterhouse waste and etc. Digestion takes place in a stirred tank. Stirring is required to maintain an even temperature and prevent foaming and sedimentation. To avoid problems with mixing, the material needs to be fine. In drier substrates liquid might need to be added in order to obtain a pumpable consistency. Various types of stirring in the digestion tank occur. The most common method is the propeller stirring (Catarina, 2011). Wet anaerobic digestion has relatively lower retention time as the movement of the micro-organisms in the solution is not impeded by solids in the digester. The main challenge of this method is that the digester volume is not effectively used and also it incurs cost due stirring.

b. Dry anaerobic digestion:

Dry digestion is a process where the substrate contains 20 to 40% TS. This process is mainly used for stackable substrates such as organic waste, solid manure and crop residues. No mixing equipment is necessary, and crust formation is not possible due to the relatively solid nature of the digester contents (Catarina, 2011). Dry anaerobic digestion relatively helps to effectively use the digester volume in waste treatment. In dry or high-solids systems, handling material at high solids concentration requires different pre-treatment and transfer equipment like conveyor belts, screws, and special pumps for the highly viscous streams. Research in the 1980's indicated that biogas yields and production rates for single-stage dry systems were as high as or greater than that of wet systems. The challenge of dry systems is handling, mixing, and pumping the high-

solids streams rather than maintaining the biochemical reactions (California Integrated Waste Management Board, 2008).

2.3. Anaerobic digestion of different wastes

2.3.1. Slaughterhouse Waste

Abattoir effluents reaching water streams contribute significant level of biochemical oxygen demand and other nutrients, resulting in eutrophication, bad odor, lose of biodiversity and etc. Slaughterhouse wastewater has a complex composition and is harmful to the environment (Masse, 2000).

It is strong as it contains high biochemical oxygen demand, chemical oxygen demand and alkalinity compared to domestic wastewater. After the initial screening of coarse solids, slaughterhouse wastewater is mainly composed of diluted blood, fat, rumen which contains a significant amount of partially digested lignocellulosic material (Iván and Liliana, 2010). The nature and composition of slaughterhouse wastewater have been discussed by Masse (Masse, 2000).

The major characteristics are high organic content mainly composed of proteins and fats, sufficient organic biological nutrients, adequate alkalinity, and free of toxic materials. Thus, slaughterhouse waste is an ideal substrate for anaerobic digestion and elimination of more than 90% chemical oxygen demand (COD) can be attained (Cuetos, et al., 2010). The high fat and protein content mean that slaughterhouse waste can be considered a good substrate for the anaerobic digestion process, due to its expected high methane yields (Palatsi, et al., 2011).

Lipids represent an important fraction of the organic charge in slaughterhouse waste (Cuetos, et al., 2010). Based on its characteristic slaughterhouse waste is very suitable and has high potential to be treated anaerobically for biogas production (Budiyono, et al., 2011).

Literatures indicate total fat removal of 61% for the SHW digestion and 83% for the co-digestion of the mixture of SHW with organic fraction of municipal solid waste (OFMSW). The addition of OFMSW to the co-digestion system contributed to a significant increase in the daily biogas yield when co-digesting with SHW along with an increase of VS in the reactors (Cuetos, et al., 2008).

2.3.2. Fruit- Vegetable Waste

Fruit and vegetable wastes (FVWs) represent a specific waste produced largely by the wholesale markets and constitute a source of nuisance in municipal landfills because of their high biodegradability (Bouallagui, et al., 2004). Since they have very high moisture contents, biochemical processes, such as anaerobic digestion, are the most suitable conversion technologies to treat FVWs (Asquer, et al., 2013). Fruits have generally C: N ratios in average three times and VS on wet basis two times higher than vegetables. Due to the presence of the main macro, micro, and trace elements, the use of FVWs in anaerobic digestion without adding additives or other organic materials as co-substrate is possible, while heavy metals are generally lacking (Asquer, et al., 2013; Bouallagui, et al., 2003). The most significant factor for enhanced FVW digestion performance was the improved organic nitrogen content provided by the additional wastes. Consequently, the occurrence of an imbalance between the different groups of anaerobic bacteria which may take place in unstable anaerobic digestion of FVWs could be prevented.

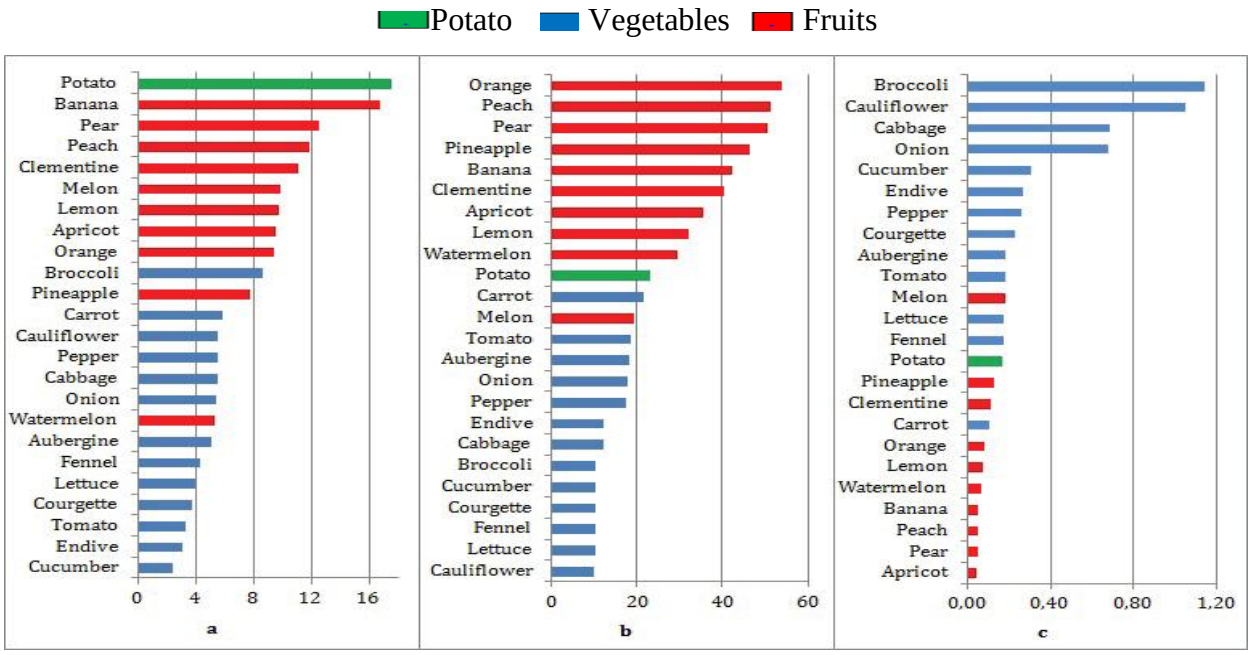


Figure 2.3: Distribution of the main substrate properties of FVWs (a) Volatile Solids content in percent on wet basis, (b) C: N ratio and (c) Sulphur content in mg/kg on dry basis (Asquer et al., 2013, p. 91).

2.3.3. Sewage Waste

Domestic sewage comprises spent water from kitchen, bathroom, toilet, etc. The pH of the fresh sewage is slightly more than the water supplied to the community. Generally the pH of raw sewage is in the range 5.5 to 8.0. Fresh domestic sewage has a slightly soapy and cloudy appearance depending upon its concentration.

As time passes the sewage becomes stale, darkening in colour with a pronounced smell due to microbial activity (De Mes and Stams, 2003). Generally nitrogen content in the untreated sewage is observed to be in the range of 20 to 50 mg/l measured as TKN. The general range of BOD observed for raw sewage is 100 to 400 mg/l (De Mes and Stams, 2003).

In general, the COD of raw sewage at various places is reported to be in the range 200 to 700 mg/l. As shown in the Figure 2.4: 85% nitrogen, 2% organic matter, 46% phosphorus and 62% potassium present in domestic wastewater originates from the urine, while 11.5% nitrogen, 52% organic matter, 35% phosphorus and 25% potassium originates from faeces. In developing countries anaerobic treatment of domestic sewage is an appropriate technology as temperatures are favorable. The maximum anaerobic biodegradability of domestic sewage is 74% (De Mes and Stams, 2003).

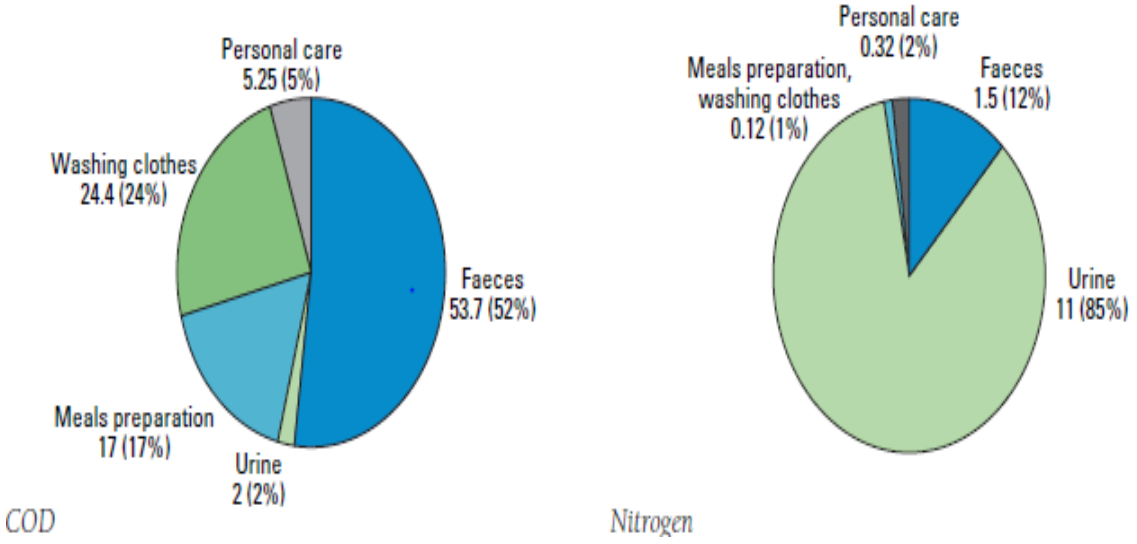


Figure 2.4: Organic matter (gCOD) and Nitrogen (g) produced in domestic wastewater per person per day (De Mes and Stams, 2003)

Domestic wastewater is composed of black water and grey water flows, which can be discharged separately or combined (De Mes and Stams, 2003):

a. **Black water:** Wastewater from flushing the toilet contains faeces, urine and cleansing materials. Black water contains a high number of pathogens. The concentration of this waste stream is dependent on the amount of flushing water used. In 'conventional' European and northern American toilets about 10 liters per flush is used. Poor flush toilets use 2 to 5 liters per flush and modern vacuum toilets only use 1 liter per flush (De Mes and Stams, 2003).
b. **Grey water:** Wastewater from in house usage such as bathing, washing and cleansing does not contain excreta and therefore less pathogens and little nutrients (N, P, K). Volumes and concentration are strongly dependent on water consumption patterns and waste handling (De Mes and Stams, 2003).

The mean production of faeces plus urine amounts to 1.5 liters per person per day. Moreover, faeces contain the largest amount of pathogens. All these compounds are diluted with clean water when flushing toilets and moreover when shower and bath water, washing water and kitchen water are added, before entering the sewer (De Mes and Stams, 2003).

2.4. Anaerobic co-digestion

Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. Substrates as food wastes, sewage waste, cattle manure, certain energy crops and algae are good bases to obtain processes with good nutrient and trace element balances. These kinds of substrates can often be implemented for "mono-substrate" digestion, while substrates dominated by carbohydrates or fats needs to be co-digested or digested in processes modified by e.g. nutrient and trace element additions, sludge recirculation, etc. The use of co-substrates usually improves the biogas yields from anaerobic digester due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates (Biogas Research Center, 2014). Co-digestion of slaughterhouse waste with other substrates can reduce organic overloading problems of nitrogen content and improvement of biodegradability. FVWs have a high content of biodegradable organic matter and a high C: N ratio, and can be beneficial in the reduction of inhibition problems of anaerobic digestion with other substrates, because the characteristics of both types of wastes are complementary (Cuetos, et al., 2010)**.** It seemed that carbohydrate rich substrates like FVW are good producers of VFAs and that protein rich substrate are yielding good buffering capacity. The high values for the methane yield and the VS reduction were indicatives for a high content of biodegradable organic matter in the co-substrate

due to an improved ratio of nutrients and better availability of the organic substances (Bouallagui, et al., 2009). The anaerobic digestion process is dependent on the growth of micro-organisms. Thus, there is a necessity to supply nutrients in sufficient amounts and at right proportions to sustain an optimal growth of the bacteria and archaea to obtain an efficient biogas production from a given substrate (Biogas Research Center, 2014).

It is clear that optimization of biogas production from any substrate should be based on an analysis of the nutrient composition to investigate the need for complements. Such needs may be taken care of by co-digestion of a combination of substrates leading to the right proportions and amounts of nutrients (Biogas Research Center, 2014).

Protein degradation increases the NH_4^+ and NH_3 levels in the reactor liquid, which above certain levels can affect the anaerobic digestion negatively. Co-digestion with other substrates or slow adjustment of the microflora to high ammonia levels in most cases solves the problem (Biogas Research Center, 2014).

Fat rich materials represent a high methane potential but with risks of accumulation of LCFA because it is toxic to anaerobic micro-organisms, particularly acetogens and methanogens. LCFAs are surface active compounds and in aqueous systems behave like synthetic surfactants. The unionized form of LCFAs adsorbs initially to the microbial cell surface and is then taken up into the cell (Salminen, 2002). An additional problem is their tendency to form floating scum causes fouled gas collection pipes. Therefore, co-digestion with more carbohydrate rich materials will likely be needed to obtain stable, efficient processes (Biogas Research Center, 2014).

Generally, there are several advantages to anaerobic co- digestion. The primary advantage is the enhancement of biogas yield. Solid wastes are converted into pumpable slurries when mixed with liquid organic wastes. This can result in easier handling both in the digestion process and afterwards. Co-digestion can help achieving a better NPK ratio by blending different organic wastes. The value of the digestate as a fertilizer is thus enhanced (Fabien, 2003).

2.5. Factors affecting biogasification

2.5.1. Temperature

Temperature is an important factor to consider in anaerobic digestion. The methanogens are inactive in extreme high and low temperatures. Enzymatic activity of the bacteria largely

depends upon temperature, which is critical factor for methane production. High temperatures kill bacteria; low temperatures cause them to become dormant. This is why the process of bio-methanation is very sensitive to changes in temperature (BSP-Nepal, 2005).

The degree of sensitivity, in turn, is dependent on the temperature range (Jan and Felix, 2010). The bacteria responsible for anaerobic digestion are classified according to these temperature ranges; thermophilic digestion occurs at proximately 45 to 60°C, mesophilic anaerobic digestion around 20 to 45°C and psychrophilic digestion at temperatures lower than 20°C. In general the growth rate of microbes under psychrophilic conditions is below their optimum and in that case the decay rate can be considered insignificant.

Figure 2.5, shows that the three temperature classes of methanogenic microbes each have an optimum growth rate; the dotted line shows an approximate exponential increase in metabolic activity at increasing temperature (Buysman, 2009).

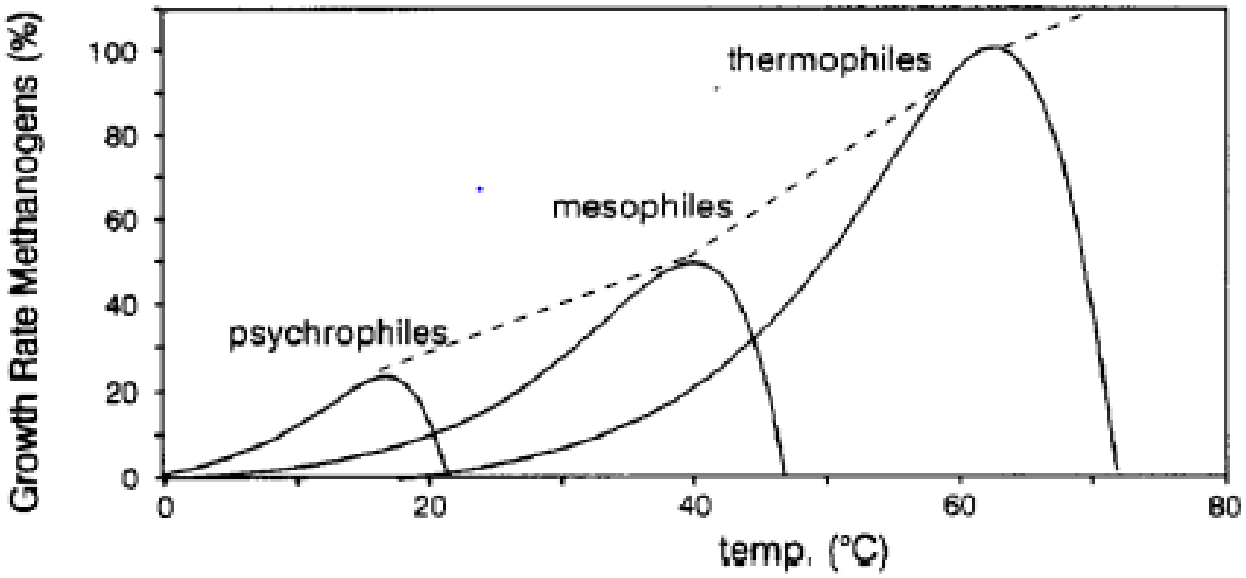


Figure 2.5: Relative growth rate of psychropiles, mesophiles and thermophiles (Buysman, 2009, p. 56)

Biogas processes are generally run at one of two different temperatures: mesophilic-37^{o}C or thermophilic- 55^{o}C (Catarina, 2011). Mesophilic and thermophilic micro-organisms grow best at these temperatures (BSP-Nepal, 2005; Culhane, 2012). Like most chemical reactions, the rate of anaerobic digestion increases with temperature. The reactions velocity doubles every 10°C between 10 and 35°C (Thibault, 2010). Gas production can be augmented significantly by

increasing the temperature up to 55°C beyond which the production falls because of destruction of bacterial enzyme by elevated temperature. Thermophilic digestion has a higher rate of digestion compared to psychropiles and mesophilic digestion. Disadvantages of thermophilic digestion include reduced stability and the need for greater process heating when compared to operating in the mesophilic temperature regime.

Furthermore, unbalanced fermentation could occur due to prolonged exposure to high temperatures, thus favoring the sulphur reducing bacteria, resulting in the formation of more hydrogen sulfide. Generally speaking, because of the additional heating requirements thermophilic digestion is only economically viable at high organic loading rates (Sue, et al., 2009).

On the other hand, when the ambient temperature goes down to 10°C, gas production virtually stops (BSP-Nepal, 2005). Gas production can be increased in the cold climate by means of proper insulation of digester. Proper insulation on top of the digester, i.e. by the placement of a haystack, helps to increase gas production in the cold season. The temperature fluctuations problem between day and night are solved by building anaerobic digester underground, since the temperature of the earth below a depth of one meter is practically constant (Jan Lam and Felix ter Heegde, 2010).

Digester painting with different color also affect rate of gas production. Gas production will be higher if the digester is painted black or red than with blue or white, because the digester temperature is increased by solar radiation (Ludwig, 1988).

2.5.2. pH

A pH close to neutral, i.e., 7, is optimum for anaerobic digesters. At lower pH values below 5.5, some bacteria carrying out the process are inhibited. The methanogens involved in the biological process of methanogenesis which is the terminal stage of anaerobic digestion require a neutral or mildly alkaline environment, as a too acidic or too alkaline environment would be detrimental. They further pointed out that a pH between 6.5 and 8 is best for methanogenesis. The pH value of the slurry in a digester depends on the carbon dioxide content in the digester (Babajide and Adelekan, 2009). The pH in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This can inhibit or even stop the

digestion or fermentation process. Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.5. Later, as the digestion process continues, concentration of NH_4 increases due to digestion of nitrogen which can increase the pH value to above 8. When the methane production level is stabilized, the pH range remains buffered between 7.2 to 8.2 (Jan and Felix, 2010).

Each group of micro-organisms involved in the anaerobic fermentation has its own optimal pH for growing. The optimum of pH for acetogens is for example around 6.6 while it is around 6.8 to 7.2 for the methanogens. Acidogens have an optimal pH around 5 to 6 and hydrolytic bacteria around 7.2 to 7.4. In a process of biomethanation in one step, it is better to maintain the pH neutral because methanogenesis often is the limiting step due to their sensibility to pH and acetogens can also work at neutral pH (Thibault, 2010).

The pH of the input substrate plays very important role in methane formation. The acidic condition is not favorable for methanogenic process. In such case the pH can be adjusted by the addition of calculated amount of lime ($CaCO_3$) as over liming is harmful to the bacteria. When nitrogenous materials are used for feeding, nitrogen is liberated in the form of ammonium hydroxide during the process of methane formation. This causes an increase in pH value of the media (BSP-Nepal, 2005).

2.5.3. Nutrient Concentration

Necessary elements such as carbon, hydrogen, nitrogen, phosphorus and many other microelements must be present in adequate quantities for the normal growth of the micro-organisms. It has been recognized that all living organisms need nitrogen for the synthesis of protein. In the absence of sufficient nitrogen, the bacteria would not be able to utilize all the carbon present and the process would be less efficient. The carbon: nitrogen (C: N) ratio expresses the relationship between the quantity of carbon and nitrogen present in organic materials. Materials with different C: N ratios differ widely in their yield of biogas. The ideal C: N ratio for anaerobic biodigestion is between 20:1 and 30:1 (Ludwig, 1988; Jan and Felix, 2010).

If C: N ratio is higher than this range, biogas production will be low, because the nitrogen content of the feed material will be consumed rapidly by methanogenic bacteria for meeting their protein requirements rather than reacting on the carbon in the material. Materials with high C: N ratio is typically the residues of agricultural plants. Conversely if C: N ratio is very low, that is

outside the ideal range, nitrogen will be liberated and will accumulate in the form of ammonia, which raises the pH value of the slurry in the digester.

Wastes vary in their C: N ratio as shown in Table 2.4. Animal waste, particularly cattle dung, has an average C: N ratio of about 24. Plant materials such as straw and sawdust contain a higher percentage of carbon. The human excreta have a C: N ratio as low as 8. Materials with high C: N ratio could be mixed with those of low C: N ratio to bring the average ratio of the composite input to a desirable level (Jan and Felix, 2010).

Table 2.4: Common feedstock and their C: N (Edison, 2014)

Substrate	C: N ratio
Cattle manure-liquid	6 to 20
Chicken manure	3 to 10
Swine manure-liquid	5
Straw	50 to 150
Grass	12 to 26
Potatoes	35 to 60
Sugar beet/beet foliage	35 to 46
Cereals	16 to 40
Fruits and vegetable	7 to 35
Mixed food waste	15 to 32
Food waste	3 to 17
Slaughterhouse waste –guts	22 to 37
Sewage waste	9-25
Digestate sewage waste	4-28
Urine	0.8
Dairy manure	5-25

2.5.4. Retention Time

Retention time is the average period that a given quantity of input remains in the digester to be acted upon by the methanogens. Like temperature, retention time is decisive factor for the survival of pathogens; pathogens are more likely to survive at low temperatures and short

retention times (Buysman, 2009). Selection of a suitable retention time depends not only on the process temperature, but also on the type of substrate used (Jan and Felix, 2010). In principle, any biodegradable materials, if fermented under anaerobic condition, can produce biogas by the action of methanogenic bacteria. Thus, retention time for cow or buffalo dung is less compared to kitchen waste (BSP-Nepal, 2005).

There is no way to calculate theoretically the optimal retention time since its value depends on the ambient temperature and of the organic material loaded in the biodigester. The higher the degradability of the organic material, the shorter is the retention time, with an optimal value. Indeed, if the retention time is too short, bacteria do not have time enough to degrade the organic material. At insufficient long retention time, the system becomes increasingly acidified because the conversion rate of VFA to methane by the methanogens is slower than the production of VFA. Consequently the VFA concentration builds up, which results in a negative feedback, inhibition of methanogenesis, because methanogens are the most sensitive of all microbes in anaerobic digestion to a decrease in the pH. When the retention time is sufficiently large, all the microbes have sufficient time to degrade the substrate and to have a net growth rate. Then, the bacteria will starve and the production of methane decreases once the optimum is exceeded (Buysman, 2009; Thibault, 2010).

2.5.5. Water

The production of biogas is inefficient if the fermentation materials are too dilute or too concentrated. With too little water, the activities of the micro-organisms will be affected and the quantity of biogas produced will be reduced. The dilution should be made to maintain an optimum total solid content. If the feed to the digester is too diluted, the solid particles will settle down into the digester and if it is too thick, the particles impede the flow of gas formed at the lower part of digester. There is also higher risk of scum formation at the top of the slurry layer. In both cases, gas production will be less than optimal. Furthermore, most biogas digesters are designed for a total solids content of about 8%. A change of this ratio will have an impact on the retention time and the hydraulic functioning of the digestion process (Jan and Felix, 2010).

2.5.6. Toxicity

Mineral ions, heavy metals, antibiotics and the detergents are some of the toxic materials that inhibit the normal growth of microbes in the digester. Mineral ions such as sodium, potassium, calcium, magnesium, ammonium and sulphur also stimulates the growth of bacteria; while very heavy concentration of these ions will have toxic effect. Inhibiting concentration of these mineral ions is indicated in Table 2.5. Ammonia is common problem of anaerobic digesters.

Inhibitory levels of 50 to 150 mg/l of free ammonia have been reported (Alvarez, 2008); however, methanogens may adapt to ammonia concentrations of several times the initial threshold level. The maximum tolerable ammonia concentration was 6.2 times higher than the initial toxicity threshold level (Alvarez, 2008).

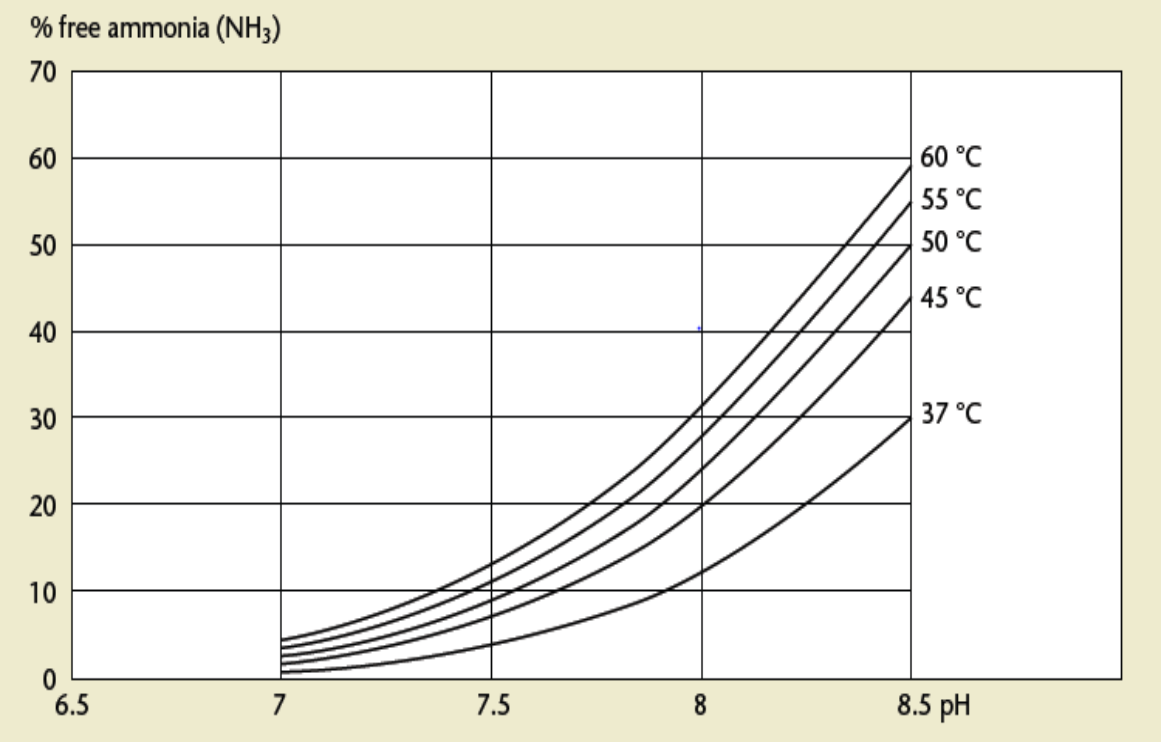


Figure 2.6: Effect of pH and temperature on the balance between ammonium and toxic ammonia (NH_4^+/NH_3) (Peter, 2009, p. 13)

In an aqueous solution ammonia is always found in equilibrium with ammonium (NH_4^+). This equilibrium is determined by the acidity, pH and temperature of the environment, and as ammonium is not as toxic as ammonia, this equilibrium is important:

$$NH_4^+ \leftrightarrow NH_3 + H^+ \quad (2.4)$$

At a high pH, the equilibrium is shifted to the right, and the environment becomes more toxic to bacteria. Higher temperatures will also shift this equilibrium to the right. This is why a thermophilic biogas process is more sensitive than a mesophilic process to ammonia inhibition (Peter, 2009).

Other important endogenous process inhibitors are the organic acids formed during the process. If these are not converted as soon as they are formed they can lead to an acidification of the process. Other substances such as heavy metals, salts and micronutrients can also inhibit the process at high concentrations.

Some of these substances are essential for the process at low concentrations; in the same way those vitamins are for humans (Peter, 2009). The inhibiting levels of some of the major ones are given in the Table 2.5.

Table 2.5: Toxic Level of Various Inhibitors (Jan and Felix, 2010, p. 16)

Inhibitors	Inhibiting concentration
Sulphate (SO_4^{--})	5000 ppm
Sodium Chloride (NaCl)	40,000 ppm
Copper (Cu++)	100 mg/1
Chromium (Cr^{+++})	200 mg/1
Nickel {Ni^{+++})	200 - 500 mg/1
Sodium (Na^{+})	3,500 - 5,500 mg/1
Potassium (K^{+})	2,500 - 4,500 mg/1
Calcium (Ca^{++})	2,500 - 4.500 mg/1
Magnesium (Mg^{++})	1,000 - 1,500 mg/1
Manganese (Mn^{++})	Above 1,500 mg/1

2.5.7. Enclosure

Biogas is formed when organic matter decomposed by anaerobic bacteria. Methanogenic bacteria need an oxygen free environment as they are obligatory anaerobic. In aerobic condition, most of these bacteria are inactive in metabolism, thus digesters should be totally airtight to maintain strictly anaerobic condition. In many places, digesters are buried in the Earth to maintain anaerobic condition (Peter, 2009).

2.6. Environmental, economic and social benefits of biogas

2.6.1. Energy and Climate Concerns

Biogas is a renewable source of energy. The carbon dioxide that is released when biogas is combusted and mixed with the oxygen in the air does not contribute to the greenhouse effect. The carbon in the methane molecule produced by the biogas process originates from carbon dioxide in the air that growing plants have previously taken up by photosynthesis.

The use of biogas is thus an important step in climate change mitigation. The development of biogas represents a strategically important step away from oil dependency that will contribute to a sustainable energy supply in the long term. Renewable means that there will be no "peak biogas"; rather biogas will be continuously available and thus offers improved energy security. Biogas is also produced locally meaning that it is not dependent on trade relationships. This also contributes to improved energy security (Lars, 2012).

2.6.2. Increase Agricultural Productivity

Anaerobic digestion increase nitrogen fixation. The digestate is used as fertilizer. Anaerobic digestion kills certain bacteria, parasites and weed seeds that otherwise might have had negative effects on crop production. Organic biogas production helps to ensure food security (Florian Gerlach, 2013)**.**

In Ethiopia, it leads to a reduction in agricultural productivity as a result of using dung and crop residue as fuel instead of using these as soil nutrients. Due to the use of dung as a source of domestic energy it is estimated that 10% of the annual grain production is lost for the Tigray region. Through the biogas programme the utilization of slurry is promoted, thus contributing to increased crop production (National Biogas Programme Ethiopia, 2008).

2.6.3. Sustainable Development

Production of biogas offers many benefits to society and is an important contribution to a sustainable development. One of the most important tasks we face today is to reduce our exploitation of the earth's finite resources and to develop systems for re-cycling of nutrients and energy that are sustainable in the long term. In the biogas process, waste is converted into energy and nutrients and hence, the exploitation of finite resources is reduced. The biogas process has

many advantages from the point of view of the environment, especially since it results in two environmentally-friendly final products: biogas and bio fertilizer (Lars, 2012).

2.6.4. Carbon Revenues

A biogas installation results in greenhouse gas (GHG) abatement. This abatement is denoted as "carbon offsets" and has a value under the clean development mechanism (CDM) or the voluntary carbon market. These offsets can be sold as carbon credits and utilized for policies to stimulate biodigester adoption, by, for instance, providing subsidies or soft loans.

Consequently, these carbon revenues can cover a part of the required capital investments to tackle the impact of the low ambient temperature on biogas production (Buysman, 2009). All the CDM certified and biogas projects under validation are studied to determine the claimed carbon reduction per digester to estimate carbon income. On average around 4.01 tCO_2eq per year per digester is claimed, higher if methane from manure management is included and less without (Buysman, 2009).

2.6.5. Biogas and Recycling of Nutrients

When biogas is produced from organic waste, manure or food waste, the residue, digestate, contains all the nutrients in the original substrate. These nutrients are retained in soluble and plant-available forms in the residue, and cannot be lost by leaching, since the digestion takes place in closed containers. Using the digestion residue as a bio fertilizer reduces the need for mineral fertilizers. The return of the bio fertilizer to arable land constitutes an excellent case of recycling of a natural resource.

2.6.6. Biogas as a Bio-fuel

Biogas is a high quality bio-fuel. As any fuel it can be used to produce electricity and heat, or both in CHP equipment. As it consists of methane it is easily adaptable to existing processes where natural gas, also methane, is used. Methane is a fuel in demand by industry, partly because it is a gas, which gives a high quality combustion that can be precisely controlled. Methane burns with a clean and pure flame, which means that boilers and other equipment are not clogged by soot and cinders.

This leads to a cleaner workplace environment and less wear and tear on the plant. Biogas is the most environmentally friendly vehicle fuel on the market today (Lars, 2012). Biogas gives the

smallest emissions of carbon dioxide and particulate matter of all vehicle fuels on the market. Emissions of carbon monoxide, hydrocarbons, sulphur compounds and nitrogen oxides are less than when petrol or diesel is used as fuel. A gas engine is quieter and vibrates less than a diesel engine, which means a better working environment for professional drivers. Biogas is lighter than air. If a leakage occurs, methane rises through the surrounding air. Biogas has a higher temperature of ignition than petrol and diesel, which reduces the risk of fires and explosions at accidents (Lars, 2012)

2.6.7. Decrease Eutrophication

If manure is just unloaded in the environment, it will leak and be carried by water to the nearest water course. Leaking manure is a main cause of Eutrophication of surface waters in the region. Besides from this, anaerobic digestion also to a great extent reduces the pathogenic contents of the manure. Also, the process greatly reduces the smell of the manure (Lars, 2012)

2.6.8. Used as Waste Management Option

Biogas is also produced with organic waste as substrate. This is a great advantage in waste management; the waste does not need to be land filled or just incinerated for recovery of its heat content. When fermenting organic waste the two important resources are recovered, the biogas and the nutrients in the residue (Lars, 2012)

2.6.9. Woman Empowerment and Health

Biogas is widely accepted in Ethiopia as a cooking fuel and will mainly benefit women and children (National Biogas Programme Ethiopia, 2008). Cooking on biogas has also a significant health advantage over traditional cooking with an open fire. The major point is the fact that cooking is smokeless and that will diminish the number of eye infections and respiratory problems among in particular women usually in charge of cooking and small children being near their mothers. Moreover, in rural area collecting fire wood takes time. Always this activity is done by women. It is expected that biogas will reduce the overall workload of women by providing the daily energy demand and increase women empowerment (National Biogas Programme Ethiopia, 2008).

Also the danger that children burn themselves while cooking is less when using a biogas stove (Jan and Felix, 2010).

2.6.10. Reduce Deforestation

The energy saving aspect and thus saving on cost for firewood is from the point of view of the farmer household an important aspect. Moreover it is one of the major considerations of a government to promote this technology because it reduces the burden on the environment. It saves trees and helps thereby to combat erosion and to store carbon (Jan and Felix, 2010). In Ethiopia, more than 90% of the energy demand of the country provided by biomass, a dire energy situation exists due to a high rate of depletion of the country's forest cover (National Biogas Programme Ethiopia, 2008).

2.6.11. Reduce Greenhouse Gas (GHG)

The conversion of animal wastes and manure to methane/biogas can yield significant health and environmental benefits. Methane is a GHG that has 21 times more global warming potential than carbon dioxide in trapping heat in the atmosphere. By trapping and utilizing the methane, GHG impacts are avoided (Sergio, 2010).

2.7. The millennium development goals (MDG) and biogas

Of the eight Millennium Development goals, domestic biogas has a very direct relation with four the main goals as discussed in (National Biogas Programme Ethiopia, 2008) and (Jan and Felix, 2010).

MDG 1: Eradicate extreme poverty and hunger

Target 1: To halve extreme poverty

Biogas plants reduce financial and economic costs expended on fuel for cooking and to a lesser extent also lighting. The produced bio-slurry is a potent organic fertilizer and may reduce the use of chemical fertilizer. In general, biogas households are not typically the ones in developing countries that suffer from extreme poverty, although many of them are poor.

However, the biogas dissemination process and the resulting reduced claim on common ecosystem services do affect the livelihood conditions of very poor non-biogas households as well through:

- Construction and installation of biogas creates employment for landless rural people.
- Biogas saving on the use of traditional cooking fuels increases the availability of these fuels for (very) poor members of the community.

MDG 3: Promote gender equality and empower women

Target 4: Eliminate gender disparity in education

Women and girls predominantly spend time and energy on providing traditional energy services. Housekeeping and absence of proper illumination creates barriers for women and girls in accessing education and information as well as their mobility and participation in 'public' activities:

- Domestic biogas reduces the workload: collection of firewood, tending the fire, cleaning soot of cooking utensils with 2 to 3 hours per household per day.
- Biogas illumination is highly appreciated for lighting, facilitating reading / education economic activities during the evening.

MDG 6: Combat HIV/AIDS, malaria and other diseases.

Target 8: Halt / reverse the incidence of malaria and other major diseases

Half of the world's population cooks with traditional (mostly biomass based) energy fuels of which the collection becomes increasingly cumbersome. Indoor air pollution from burning of these fuels kills over 1.6 million people each year, out of which indoor smoke claims nearly one million children's (<5) lives per year.

Diseases that result from a lack of basic sanitation, and the consequential water contamination, cause an even greater death toll, particularly under small children (<5 mortality caused by diarrhea is approximately 1.5 million persons per year):

- Biogas stoves substitute conventional cook stoves and energy sources, virtually eliminating indoor smoke pollution and, hence, the related health risks (e.g. respiratory diseases, eye ailments, burning accidents).
- Biogas greatly reduces the workload involved in the collection of traditional cooking fuels like wood.
- Biogas significantly improves the sanitary condition of farm yard and its immediate surroundings, lowering the exposure of household members to harmful infections generally related with polluted water and poor sanitation.
- Proper application of bio-slurry will improve agricultural production (e.g. vegetable gardening), thus contributing to food security for the community.

MDG 7: Ensure environmental sustainability. Domestic biogas can help to achieve sustainable use of natural resources, as well as reducing (GHG) emissions, which protects the local and

global environment. Application of bio-slurry increases soil structure and fertility, and reduces the need for application of chemical fertilizer.

Target 9: Integrate the principles of sustainable development into country policies and program and reverse the loss of environmental resources. Particularly larger biogas dissemination programmes have a considerable governance component. As such, they positively influence national policies on sustainable development.

Target 10: Halve the proportion of people without sustainable access to safe drinking water and basic sanitation. Biogas reduces fresh water pollution as a result of improved management of dung. Connection of the toilet to the biogas plant significantly improves the farmyard sanitary condition (National Biogas Programme Ethiopia, 2008; Jan and Felix, 2010).

2.8. Biogas production performance and experiences

The energy released during the degradation steps, which was originally stored in the substrate, is predominantly recovered by the CH_4 formed. In practice, the CH_4 production potential of livestock slurries is assessed on the basis of the content of volatile solids (VS) in the slurry and empirical standards for the production of CH_4 per g of VS (California Integrated Waste Management Board, 2008).

In anaerobic digester, volatile solid is broadly associated with digestible biomass that will be converted to gas. This assumes that volatility is a proxy for biodegradability, but lignocellulosic material tends to be less biodegradable than other volatile compounds. A better proxy for biodegradability is the five day biological oxygen demand (BOD_5), but the standard method for measuring the BOD_5 content of a feedstock takes too long to be used for measuring the ongoing biogas yield of a digester, thus it is rarely reported in the literature (California Integrated Waste Management Board, 2008).

Therefore, the scientific literature typically reports yield in terms of methane yield per dry weight of volatile solids. Typical gas yields for some organic substrates are shown in Table 2.6. Poultry manure generated high biogas yield than others substrates. This imply that this waste relatively contain high volatile solids.

Table 2.6: Typical biogas yields from various types of manure and biomass (Sue, et al., 2009; Lars, 2012)

Substrate	Range of biogas yield (liters/gVS)	Mean biogas yield (liters/gVS)
Pig manure	0.034 - 0.055	0.045
Cattle manure	0.015 - 0.035	0.025
Poultry manure	0.031- 0.062	0.046
Horse manure	0.02 - 0.035	0.025
Sheep manure	0.01 - 0.031	0.02
Cereal straw	0.018–0.032	0.025
Fodder sugar beets	0.0344–0.0982	0.081
Vegetable residues	0.03–0.04	0.041
Sewage sludge	0.031–0.064	0.035

Several researchers have been studied biogas production from different wastes and according to their report biogas yield is in the range of 0.036 l/gVS to 0.09 l/gVS added. A relatively high biogas yield, indicate that high digestibility of the feedstock and good conversion efficiency in the digester (California Integrated Waste Management Board, 2008).

This value is further optimized by anaerobic co-digestion. The performance of the reactors was evaluated by estimating destruction of total and volatile solids and by monitoring daily gas production (Dhanalakshmi, 2012).

According to Khalid, et al. (2011), co-digestion of fruit - vegetable waste with slaughterhouse wastewater and sewage waste differ in their biogas production rate and methane yield. Co-digestion of fruit - vegetable waste with sewage waste observed had high biogas production. Similarly, co-digestion of municipal solid wastes with fat, oil and grease waste from sewage treatment doubles biogas production rate and also increase methane yield when compared it's co-digestion with fly ash. Biogas production rate and methane yield of different waste co-digestion is summarized in Table 2.7.

Table 2.7: Biogas yield of different waste co- digestion (Khalid, et al., 2011)

Substrate	Co-substrate	Biogas production rate (l/day)	Methane yield (l/gVS)
Cattle manure	Agricultural waste and energy crops	2.70	0.062
Fruit - vegetable waste	Slaughterhouse wastewater	2.53	0.061
Municipal solid waste	Fly ash	6.50	0.022
Municipal solid wastes	Fat, oil and grease waste from sewage treatment	13.6	0.035
Pig manure	Fish and bio-diesel waste	16.4	0.062
Potato waste	Sugar beet waste	1.63	0.068
Sewage waste	Fruit - vegetable waste	4.40	0.06

2.9. Biogas production in Ethiopia: trends, challenges and opportunities

The energy sector in Ethiopia constitutes the traditional energy sub-sector which supplies over 90% of the energy requirements and the modern energy sub-sector provides less than a tenth of total energy supply but growing at an unprecedented rate, especially regarding the hydropower development. The energy sector in Ethiopia is composed of three main sub-sectors: biomass, petroleum and electricity. Energy consumption is very low, with an estimated total per capita consumption of only about 0.2 tone oil-equivalent (National Biogas Programme Ethiopia, 2008). Biogas is widely accepted in Ethiopia as a cooking fuel and will mainly benefit women and children. To promote the uptake of domestic biogas, a National Biogas Programme (NBP) developed to disseminate domestic biogas and develop a commercially viable market biogas sector in four selected regions: Tigray, Amhara, Oromia and SNNP regions in Ethiopia. Institutions and organizations with specific roles and responsibilities encouraged to participate in the development of a national biogas sector. The number of family-sized domestic biogas plant will increase by 14,000 in selected regions over a period of 5 years. Although the country has abundant energy resources, its potential is not yet well developed due to lack of capacity and investment (National Biogas Programme Ethiopia, 2008).

3. MATERIALS AND METHODS

3.1. Materials

Slaughterhouse waste and Sewage waste were collected using plastic bottles from Addis Ababa Abattoir Enterprise located at Kera and from summit condominium septic tank respectively. In addition, fruit-vegetable waste was collected using plastic bags from Piassa fruit-vegetable market. To start up the digestion process 1% v/v animal manure digestate from anaerobic digester found around Zenebework Alert Hospital in Addis Ababa was used as innoculum.

Buffer solution, distilled water, COD reagent, tap water, NAOH (0.1 N), HCL (0.5 N), nitrification inhibitor B (Allyl Thiourea or ATH) and KOH were chemicals used during wet anaerobic digestion experimental analysis. Table 3.1 shows list of equipments used.

Table 3.1: List of equipments used

Equipment	Manufacturer (Model)	Application or purpose
Oven	Memmert, Germany (100-800)	TS
Furnace	H.Jurgens and Co. Germany, Type VMK3	VS
pH meter	Designed and manufactured in UK, JENWAY 3505	pH
BOD incubator	Austria, TS 606/ 4-i	BOD_5
COD digester	HANNA instruments Italy	COD
Digital balance	Bosch wägesysteme GmbH, Germany	Weight
Nitrogen digester	GGerhardt WacTECH projects	Nitrogen
Distillation kit	Not analyzed	Nitrogen
Gas analyzer	GEOTech, GA5000	$\%CH_4$,$\%CO_2$, $\%H_2S$, $\%O_2$
Plastic bottles	Not analyzed	Digester
Water bath	HWS24,temperature fluctuation $\pm$0.5°C	For 37°C and 45°C temperature levels
Syringe and needle	Not analyzed	Biogas volume

Table 3.1: Continued

Vacuum pump	KNF Laboport	To pre-suck air bags
Valves	Not analyzed	To control gas flow lines
Air bag	Not analyzed	To collect biogas
Airtight bushes	Not analyzed	To form anaerobic system inside digester
Juicer	Not analyzed	For FVW size reduction
t-shape connector	Not analyzed	Connector
crucibles, desiccator, graduated cylinders, fume cooling hood,	Not analyzed	Miscellaneous

3.2. Methods

In laboratory different analysis were carried out to characterize the samples and the biogas product. General experimental workflow is given Figure 3.1.

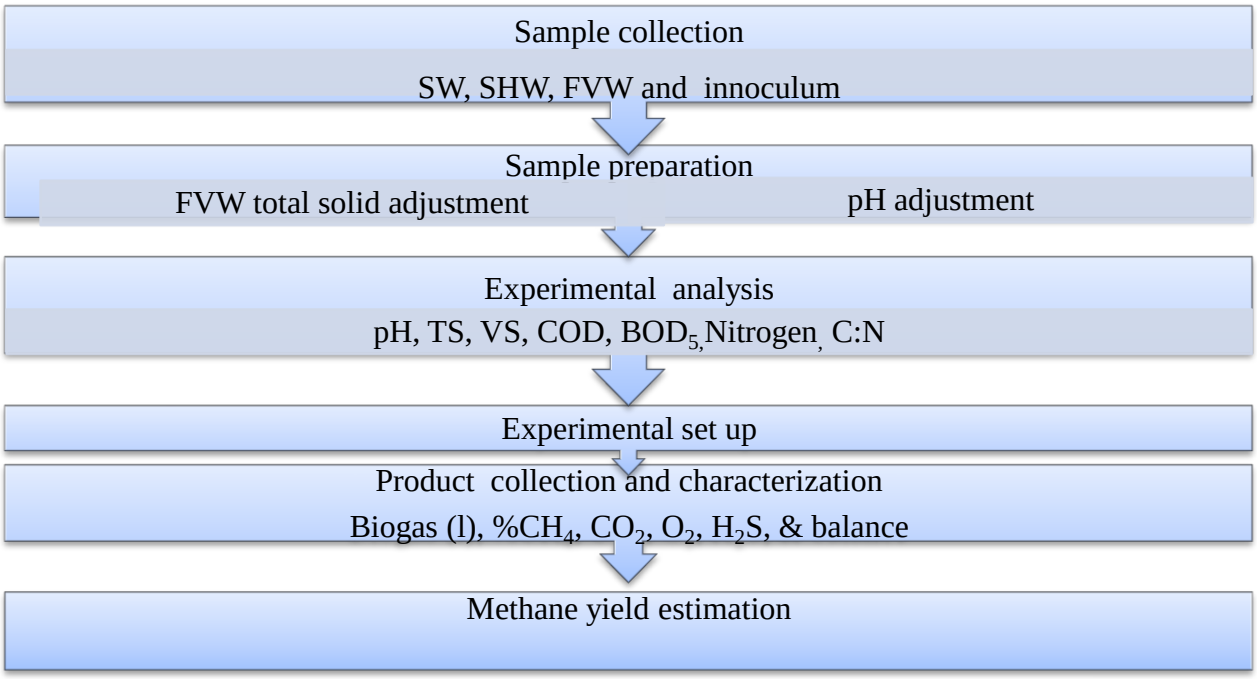


Figure 3.1: Experimental workflow

3.2.1. Sample Preparation

Total solids concentration for the fruit vegetable waste was observed greater than 12% that is upper threshold limit for wet digestion (Catarina, 2011). Thus, For FVW, its total solid was first determined by drying at 103°C until constant mass was observed on drying. The amount of water to be added to FVW to adjust its total solids concentration to 8%, which is optimum for wet anaerobic digestion, was computed from the following simple mass balance.

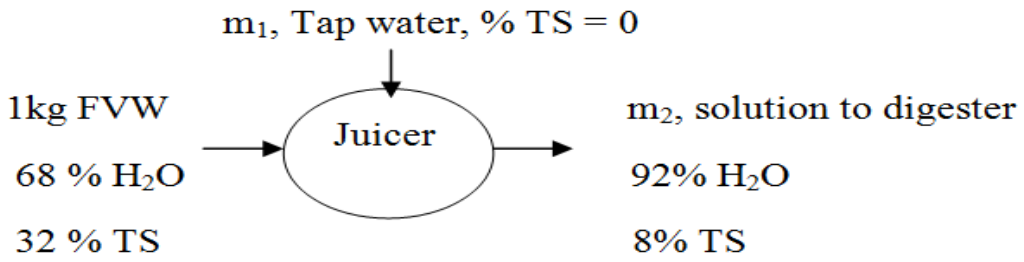


Figure 3.2: Mass balance around Fruit-Vegetable waste juicer

This adjustment was further help to easily measure the pH of fruit-vegetable waste. According to the above material balance three liters of tap water was added to a kilogram of fruit-vegetable waste to prepare 8% total solid solution.

Finally sewage, slaughterhouse, fruit-vegetable wastes and their mixtures samples were characterized in terms of pH, total solids, volatile solids, Chemical oxygen demand, total nitrogen, biochemical oxygen demand and C: N ratio before they were fed to the digesters. Then there were measured for its volume before it was fed to the digester.

3.2.2. Experimental Analysis

3.2.2.1. pH

The pH of samples was measured using laboratory pH meter. This pH meter was first calibrated at neutral pH and stands inserted into 4 pH buffer solution, which is best for the single glass electrode according to 4500-H^+ B standard (APHA, 1999). The electrode of pH meter was inserted to the aqueous sample solution and the reading was taken.

3.2.2.2.Total Solids (TS)

First the crucibles was cleaned, dried in the oven and weighted. Then the sample was added to the crucible and weighted again. According to the Standard Methods for the Examination of

Water and Wastewater 2540 B (APHA, 1999) oven was switched on and allowed to reach 103 °C. Crucible with each sample type was placed in the oven and allow to dry overnight to ensure constant weight on sample dry. The dried sample was weighted immediately to avoid absorption of moisture due to its nature. Finally the following calculation was computed to determine total solids in the sample.

$$\% \text{ TS} = \frac{W_{DS}}{W_{WS}} \times 100 \quad (3.1)$$

Where,

%TS percent of total solids

W_{WS} Weight of wet sample in gram

W_{DS} Weight of dry sample in gram

W_{DC} Weight of dry crucible in gram, and

$$W_{WS} = (W_{DC} + W_{WS}) - W_{DC} \quad (3.2)$$

$$W_{DS} = (W_{DC} + W_{DS}) - W_{DC} \quad (3.3)$$

Percent total solids value can be converted to mg/l as indicated in Equation 3.4.

$$\text{TS (mg/l)} = \frac{W_{DS}(g) \times 1000 \text{ mg/g}}{V(ml) \times l/1000 \text{ ml}} = \frac{1000000 \text{ mg}}{V(l)} \times W_{DS} \quad (3.4)$$

3.2.2.3.Volatile Solids (VS)

Sample dried at 103^{o}C was further heated in the muffle furnace at 550^{o}C for 15 to 20 minutes 2540 E (APHA, 1999). The crucible was cooled in the desiccator and weighted. The percent volatile solid was determined according to the Equation 3.5.

$$\%VS = \frac{W_{VS}}{W_{DS}} \times 100 \quad (3.5)$$

where,

%VS percent of volatile solids

W_{VS} Weight of volatile solids

W_{DS} Weight of dry sample at 103^{o}C, and

$$W_{VS} = W_{DS} - \text{Ash} \quad (3.6)$$

3.2.2.4.Chemical Oxygen Demand (COD)

This analysis was done according to DIN ISO 15705. The test tube which contains standard reagent (COD/DCO/CSB 0-1500ppm) was shacked and slowly 2 ml test sample was poured to the test tube. Then the cap screwed securely on test tube, placed into safety bottle and shacked. The tube placed into heating block at 148°C for two hours and allowed to cool. Finally the test tube was shacked again, cleans outside and measured using COD reading hatch.

3.2.2.5.Total Nitrogen

The total nitrogen in the sample was determined using the Kjeldahl method. This method has three main steps. These are digestion, distillation and titration. One gram sampled and 6 ml of concentrated H_2SO_4 was added in tecator tube and mixed carefully. Then 3.5 ml of H_2O_2 was added step by step. Violent color due to reaction was observed. As soon as the violent reaction has ceased the tube was shaked by hand. After adding 3g catalyst mixture the sample was stand for 5 to 15 minutes in the tecator rack before digestion. Then the digester switched on and waits until it reaches 370°C. As the digester gain this temperature place the rack in it and continue digestion for about 4 hours until clear solution was observed.

The tube in the rack was transferred to the fume hood for cooling. About 50 ml distill water was added and shaked by hand to avoid sulphate precipitation in the solution. At this time 25 ml 40% NAOH solution was added into digested and diluted solution. Then 250 ml conical flask containing 25 ml of boric acid, 25 ml of distilled water and indicator solution was placed under the condenser of the distiller with its tip immersed into the solution and the distillation continued for about 8 minutes until a total volume become between 200 ml to 250 ml. Finally the solution was titrated using 0.1N HCl to a reddish color. Calculation:

$$\% \text{ Nitrogen } (N_2) = \frac{V \times 0.1 \times 14 \times 100}{W_o} \quad (3.7)$$

where,

V	Volume of HCl in Liter consumed to end point of titration
W_o	Sample weight on dry matter basis and
14	The molecular weight of nitrogen
0.1	Normality of HCl

3.3.2.6. Biochemical Oxygen Demand (BOD_5)

Biochemical oxygen demand is the amount of dissolved oxygen needed by aerobic organisms in water body to break the organic materials present in given water sample at 20°C over five day incubation. To determine BOD_5 in the laboratory, first the pH of the sample was adjust at about neutral. Then 157ml sample was poured in the BOD bottle and five drops of Nitrification inhibitor B (Allyl Thiourea or ATH) and four drop of 45% KOH solution was added. The bottle cap was tightly closed by placing plastic gasket that absorbs carbon dioxide and then placed into BOD incubator for five days. This BOD incubator gives reading in mg O_2/l.

3.3.2.7. C: N ratio

Once the values of total carbon which is equal to chemical oxygen demand in the sample and total nitrogen were determined in the laboratory, C: N ratio of the substrate was calculated according to the following relation:

$$\text{C: N ratio} = \frac{\text{COD}}{\text{N}} \tag{3.8}$$

where,

COD Chemical Oxygen Demand (mg/l) and

N Total nitrogen (mg/l)

The mixture was designed based on the C: N ratio value of each substrate. Fixing the value of mixture C: N ratio at 20:1, the amount of each substrate to be added was determined iteratively using the following Equation:

$$\text{Mixture C: N ratio} = \frac{\text{SW(ml)}\times \text{C:N} + \text{SHW(ml)}\times\text{C:N} + \text{FVW(ml)}\times\text{C:N}}{\text{Digester effective volume}} \tag{3.9}$$

where,

Digester effective volume = 1.5 liters anaerobic digester used in this experiment.

Using Equation 3.9, 500 ml of sewage, slaughterhouse and fruit-vegetable waste used to form mixture from these wastes at 20:1 Carbon to nitrogen ratio. Carbon to nitrogen ratio value of 20:1 was preferred because of the following reasons during mixture design. This C: N ratio value is in the optimum range. It was observed that about 2 to 3 trucks/year FVW collected from Piassa

fruit-vegetable market. To utilize this waste using wet anaerobic digesters, it's C: N ratio should be reduced by mixing with sewage and slaughterhouse wastes as these wastes have relatively low C: N ratio. On the other hand, sewage waste and slaughterhouse waste had relatively low total solids. The amount of water needed to reduce total solids of fruit vegetable waste (as indicated in Figure 3.2) was achieved simply by mixing this waste with sewage and slaughterhouse wastes.

3.2.3. Experimental Set-up

Plastic bottles of 3 liters capacity were used both as a digester and to collect sample for laboratory analysis. Two water bathes were used at a temperature of 37°C and 45°C. Each sample was collected from their corresponding sample site and analyzed for their pH, VS, TS, BOD, COD and nitrogen. Mixture was prepared from 500 ml of sewage, slaughterhouse and fruit-vegetable wastes. Then 1.5 liters of each sample and 15 ml innoculum (1% v/v) measured and fed to the 3 liters capacity plastic bottles. Vacuum pump was used to pre-suck air inside the plastic bottles. The experiment was done during February using total of 12 aforementioned capacity plastic bottles. Four bottles containing SW, SHW, FVW and mixture placed at Room. Also 4 plastic bottles containing SW, SHW, FVW and mixture placed at 37°C and the rest at 45°C temperatures water bathes. These bottles were closed using drilled air tight bushes to create anaerobic conditions in it. Glass tubes were tightly fitted to the drilled holes of air tight bushes and extended using stretchable tubes which are directly connected to the air valves. Afterward, water bath was set at 37°C and 45°C, and the plastic digesters effective volume was fully immersed in this bath.

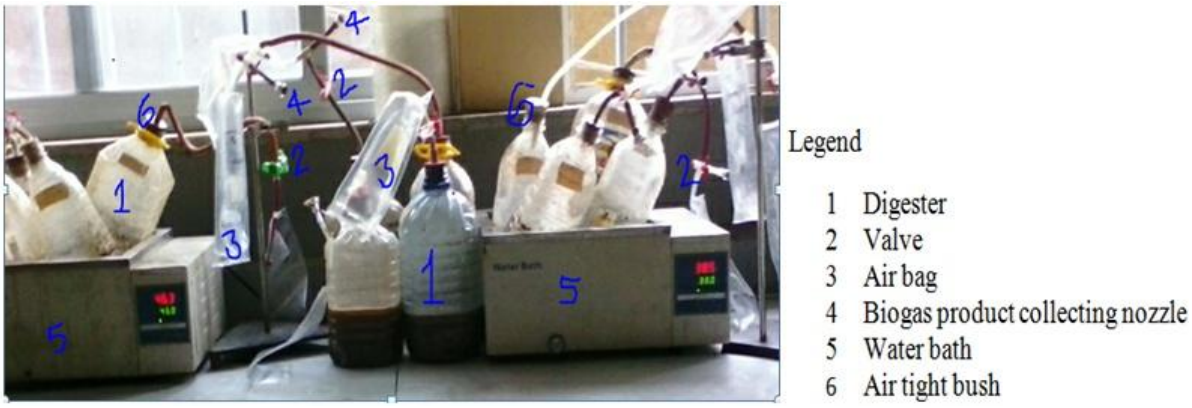


Figure 3.3: Laboratory experimental set-up

Valve was used to control gas flow from digester to air bag during digestion or to syringe. During digestion time, the valve is opened to allow biogas collection in the air bag. The volume of biogas produced was measured using graduated syringe and temporarily stored inside pre-air sucked air bag which was later connected to gas analyzer to determine CH_4, CO_2 and H_2S compositions in biogas. At this time the gas flow line from digester to the air bag was closed whereas the gas line from the air bag to the syringe was opened.

3.3. Product Characterization

The amount biogas generated and its $\%CH_4$ measurement was started after six days of anaerobic digestion and then always by allowing a day gap between successive measurements to collect sufficient biogas for analysis. Percent methane in biogas was analyzed using GEOTech gas analyzer.

This gas analyzer helps to quantify the percent composition of CH_4, CO_2, O_2, H_2S and balance in the biogas. Biogas produced was collected from 12 digesters using syringe was directly connected to the gas analyzer for its composition analysis.

3.4. Methane Yield

The amount of biogas produced and collected in air bag was measured using graduated syringe of 100ml capacity. Based on the amount of volatile solids consumed by the micro-organisms during the digestion period in the digester, methane yield for each substrate was calculated using Equation 3.10.

$$CH_4 \text{ yield (l/g VS)} = \frac{\text{Sums of } CH_4 \text{ produced (l)}}{\text{VS(g) fed}} \tag{3.10}$$

gVS = total solids in the digester (g) × change in %VS = TS × ($VS_i - VS_f$). Equation 3.10 can be written as:

$$= \frac{\sum_{i=6}^{n=30} Bg_i \times \%CH_{4\,i}}{TS \times (VS_i - VS_f)} \tag{3.11}$$

where,

VS_i % Volatile solids of fed,

VS_f %Volatile solids of digestate

Bg_i Biogas in liter of each run

$\%CH_{4i}$ percent methane of each run

3.5. Experimental Design

This study was aimed to analyze the effects of temperature (°C), retention time (days) and waste type on the biogas production (liter), and its $\%CH_4$ compositions as responses to the factors of the study. These factors were selected to achieve specific objectives of this thesis work. Moreover, literatures indicate that selection of a suitable retention time depends not only on the process temperature, but also on the type of substrate used. The higher the degradability of the organic material, the shorter is the retention time, with an optimal value. Enzymatic activity of the bacteria largely depends upon temperature, which is critical factor for methane production. High temperatures kill bacteria; low temperatures cause them to become dormant. Biogas production rate and methane yield vary between different substrates. A relatively high biogas yield, indicate that high digestibility of the feedstock and good conversion efficiency in the digester.

Table 3.2: Experimental Design Summary

Study Type		Factorial	Observations	156
Initial Design		Full Factorial		
Response	Name	Units		
	Biogas	liter		
	CH4	%		
Factors	Units			levels
Retention time	Day	6, 8,10,12,14,16,18,20,22,24,26,28 & 30		13
Temperature	°C	Room temperature, 37°C & 45°C		3
Waste type	Type	SW, SHW, FVW & M		4

Full factorial experimental design used to analyze the effect of the three factors: temperature, retention time and waste type on the biogas production (liter) and its $\%CH_4$ composition as responses. About 156 data results were observed from 12 digesters within 30 days of retention time. The data from the experiment was analyzed and modeled using Design-Expert version

6.0.8 (Stat-Ease, 2002). Analysis of variance (ANOVA) table, normal % probability versus residuals graph, and predicted versus actual values graph were used to diagnose the experimental data.

Furthermore, to visualize the combined effects of the three factors, $\%CH_4$ biogas composition versus retention time graphs at Room, 37°C and 45°C temperature levels of the four wastes under study were generated and used for discussion.

The significant terms in the models were identified by analysis of variance (ANOVA) were used for comparison of means of each response. Significance was judged by determining the probability level that the F-statistic calculated from the data was less than 5%. Significance was accepted at 0.05 level of probability ($p<0.05$). Excel was used to generate histograms to illustrate biogas production (liter), H_2S production (ppm) and methane yield from SW, SHW, FVW and M.

4. RESULTS AND DISCUSSIONS

4.1. Waste Sample Characterization

Sewage, slaughterhouse, fruit-vegetable wastes and their mixture were characterized by following a number of different standard procedures listed for each parameter. The summary of samples analysis is given in Table 4.1.

Table 4.1: Waste Sample Characterization

Parameters	Waste Type			
	SW	SHW	FVW	M
TS (%)	4.43	5.89	8.00*	6.25
VS (as %TS)	74.54	87.46	88.59	83.61
BOD5 (g/l)	0.88	7.93	9.95	9.58
pH	7.73	7.12	6.87	7.22
COD (g/l)	1.39	10.42	12.45	8.22
TKN (g/l)	0.07	0.89	0.40	0.41
C:N	18.76	11.66	31.12	20*

*represent ideal value for biogas digesters

Total solids concentration is one among most important waste characteristics. As indicated in Table 4.1, SW has relatively low %TS. This is due to more water from toilet flush, bathroom and hand wash. According to Catarina (2011), If the value of TS concentration is too high as for FVW, it impede the flow of gas formed at the lower part of digester, higher risk of scum formation at the top of the slurry layer, and the feed is not pumpable. Similarly, if the waste is too diluted relatively like SW, the digester is not fully utilized as more volume occupied by water with none substrate value. In both cases, gas production result is less than optimal.

Among the three wastes in Table 4.1, SHW contain relatively high VS. Volatile solids are portion of percent total solids that expected to be converted to the biogas and this support the fact that most literatures present CH_4 yield in terms of volume of methane per gram VS digested. Furthermore, it contains high total Kjeldahl nitrogen due to blood, rumen and fats in it. This result in lowest C: N ratio value of SHW.

In contrast, FVW contain lowest total Kjeldahl nitrogen and highest C: N ratio among studied wastes. From their C: N ratio value, SHW digestion can face nitrogen inhibition due to nitrogen accumulation which in turn raises the pH value of the slurry in the digester (Jan and Felix, 2010) where as nitrogen content of the FVW feed can consumed rapidly by methanogenic bacteria for meeting their protein requirements rather than reacting on the carbon in the material. The C: N ratio value of SHW and FVW indicate these wastes were complimentary to each another and co-digestion of these wastes can be result in optimum biogas production.

Cuetos, et al. (2008) previously characterized SHW and OFMSW and shown that SHW were rich in proteins and fats with similar nitrogen and solids contents, while OFMSW had lower total nitrogen, TS and VS, with a much higher C: N ratio, causing an increase in the organic carbon of the mixture. Thus, an improvement of biogas production stability could be expected from the mixture.

Wastes under this study also differ in their pH value. Fruit vegetable waste was observed as an acidic and sewage waste is basic. These wastes can neutralize each other on mixing and again this is an opportunity to co-digestion.

4.2. Biogas production from anaerobic digesters

4.2.1. Effect of Temperature, Retention Time and Waste Type on Biogas Production

Based on the experimental result, at room temperature lower biogas production was observed. At this temperature, maximum biogas production: 0.98, 1.38, 1.3 and 1.17 liters was collected after 18 days of retention time from SW, SHW, FVW and M, respectively as indicated in Figure 4.1 (a). At room temperature SHW, FVW and M generated high biogas after 20 days of retention time. In other words, green line indicated increasing trend. This implies the substrate was start consuming and needs extra time to reach maximum point on biogas production.

At 37°C, maximum biogas production of 1.46, 1.54, 1.32 and 1.66 liters was generated from SW, SHW, FVW and M, respectively between 8 and 16 days retention time (Figure 4.1 (a)). Comparatively, 45°C temperature level examined had more biogas production rate. Because according to Sue, et al. (2009), gas production can be augmented significantly by increasing the temperature up to 55°C beyond which the production falls because of destruction of bacterial enzyme by elevated temperature.

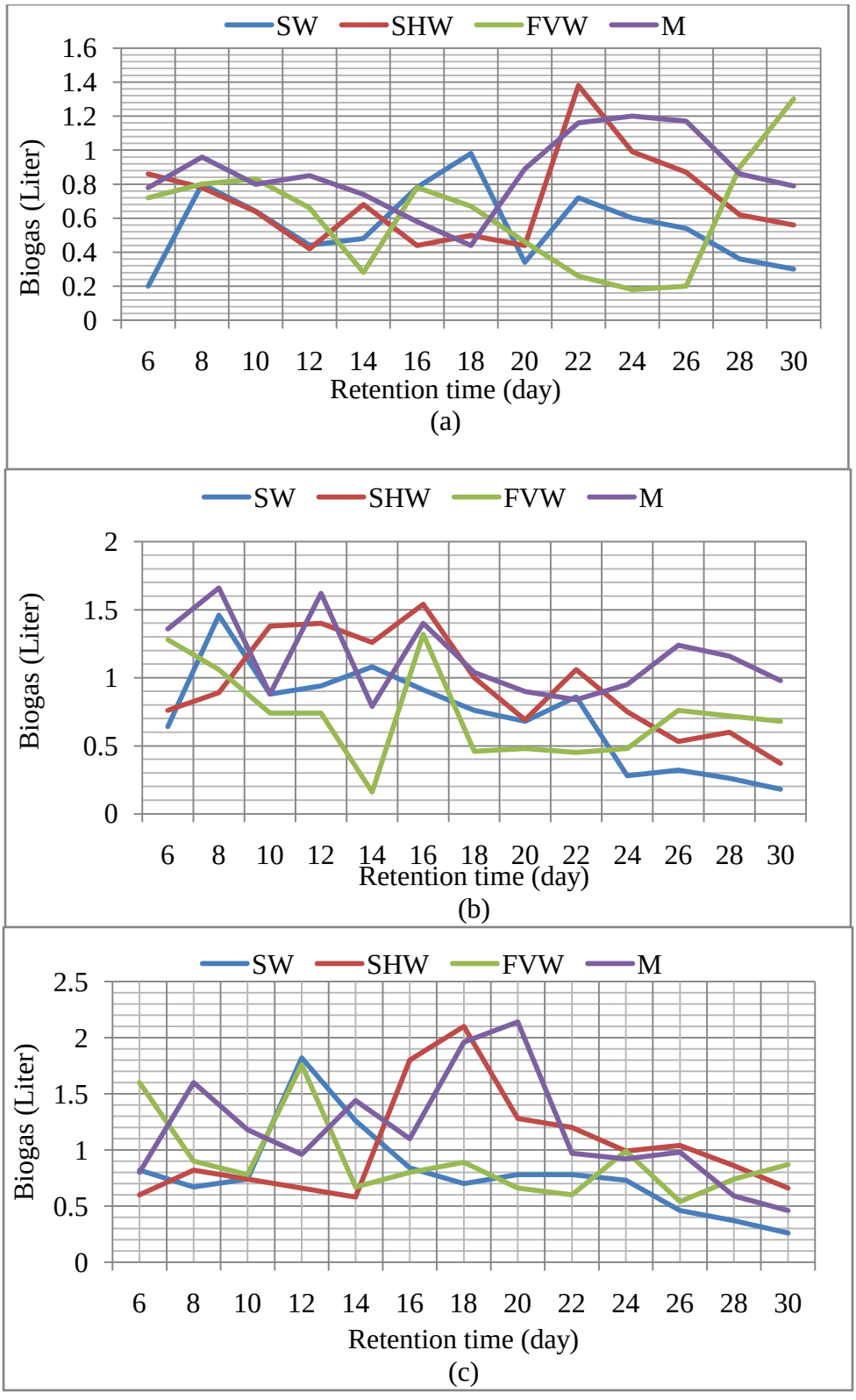


Figure 4.1: Biogas produced at (a) Room temperature, (b) 37°C, (c) 45°C

As shown in the Figure 4.1 (c), at 45°C temperature 1.82, 2.1, 1.76 and 2.14 liters biogas was produced from SW, SHW, FVW and M respectively between 12 and 20 days retention time. At both 37°C and 45°C, rough graph lines indicated decreasing trend imply waste (substrate) in digester consumed. Summary of anaerobic digesters result is given in Appendix B.

To reveal which substrate generates more biogas at room, 37°C and 45°C temperature levels, biogas produced from 12 plastic anaerobic digesters of SW, SHW, FVW and M within 30 days retention time was added for each temperature levels. Total value of biogas produced was indicating that biogas production is increasing with temperature irrespective of waste type. Like most chemical reactions, the rate of anaerobic digestion increases with temperature as described by (Thibault, 2010). Comparatively, mixture was observed to generate high biogas: 11.22, 14.82 and 15.1 in liter at room, 37°C and 45°C, respectively (Figure 4.2 and Appendix D).

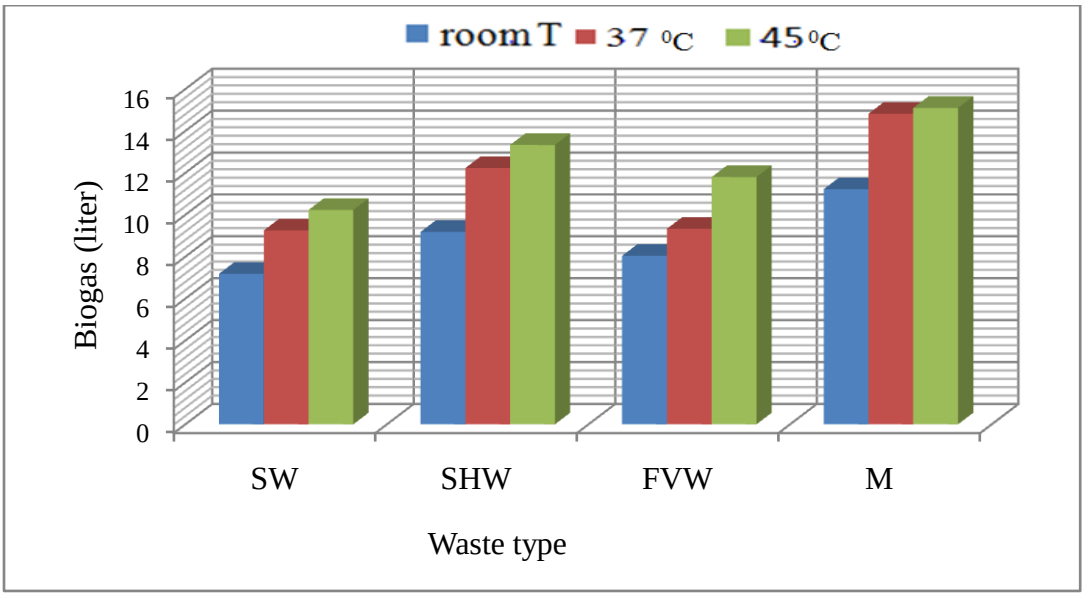


Figure 4.2: Total biogas production in liter of anaerobic digestion

4.2.2. Effect of Temperature, Retention Time and Waste Type on Biogas Methane Composition

From the laboratory experimental analysis, it was observed that for the three temperature levels, there were augmented in the percent methane composition of biogas irrespective of the waste types. On the other hand, M generated biogas with more $\%CH_4$. Slaughterhouse waste was characterized in its low C: N ratio value and inhibition due to ammonia accumulation is expected. Despite, its low C: N ratio, SHW produced maximum of 61.3, 63.6, and 73.2 $\%CH_4$

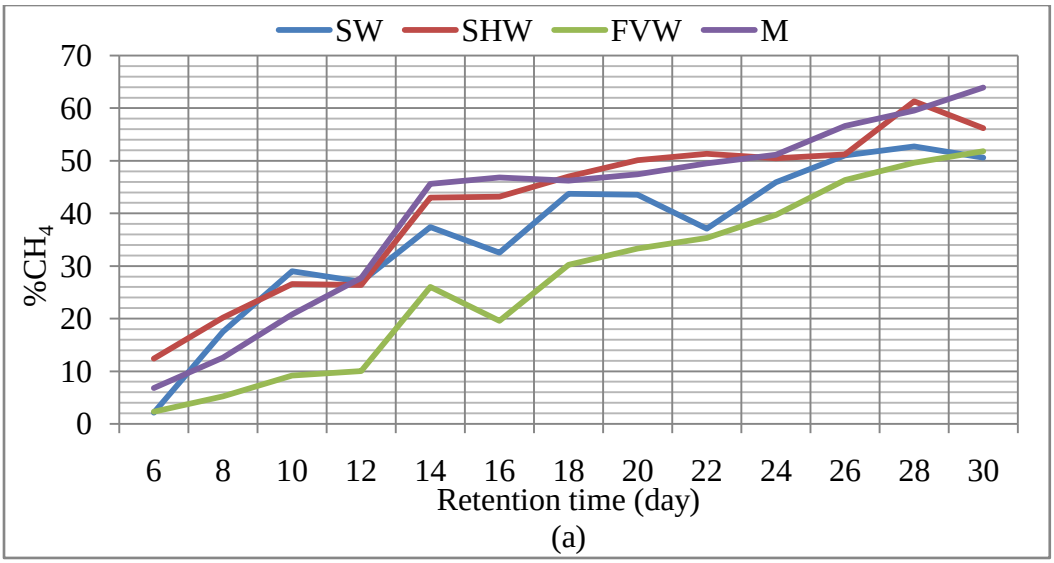
between 22 to 28 days of retention time at room, 45°C and 37°C anaerobic digestion temperatures, respectively. This is due to ammonia adaptation of methanogens. Inhibitory levels of 50 to 150 mg/l of free ammonia have been reported (Alvarez and Lide´n, 2008); however, methanogens may adapt to ammonia concentrations of 6.2 times the initial threshold level.

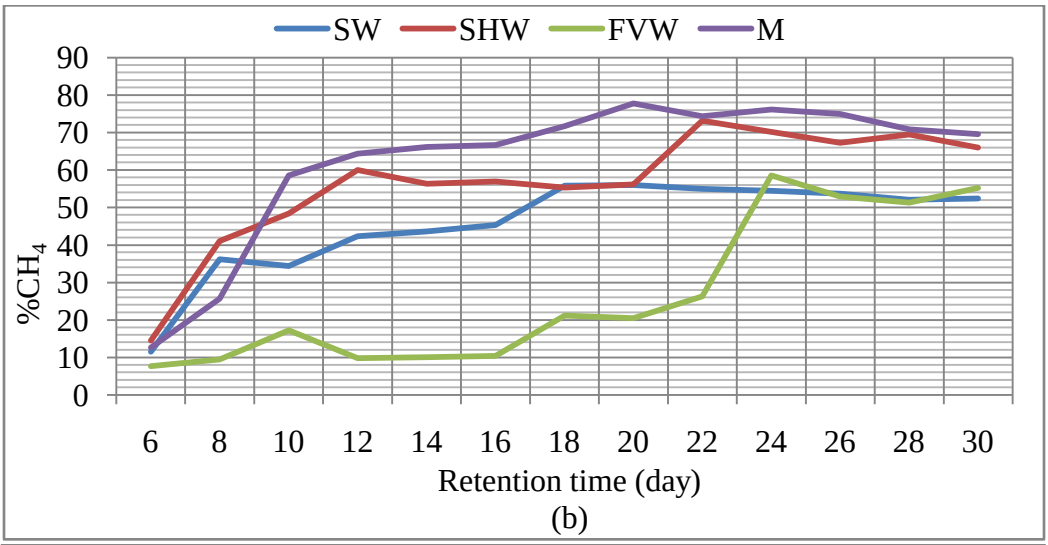
Batch tests performed by Palatsi, et al. (2011) on characterized SHW reported shows that high methane potentials, despite the inhibition the system was able to recover methanogenic activity and finally to degrade the substrate by an adaptation phenomenon. The adaptability of anaerobic micro-organisms to a fat-and free ammonia-rich medium was observed by pre-exposing the cultures to non-inhibitory concentrations (Cuetos, et al., 2008).

Regardless of easy biodegradable organic matter content and high moisture of FVW, anaerobic digestion of this waste was observed to generate 51.8, 58.6, and 63.2 %CH_4 at Room, 37°C, and 45°C digesters temperature, respectively. Decreases in pH were recorded in anaerobic digesters of this waste due to formation of VFAs. Preliminary work done by Bouallagui, et al. (2003) on anaerobic treatment of FVW in a batch digester was indicating that biogas production was inhibited by the VFAs accumulation and irreversible decreasing in pH problems.

Percent CH_4 composition versus solid retention time was plotted for SW, SHW, FVW, and M at three experimental anaerobic digesters working temperature levels. At room temperature, minimum 2.1 %CH_4 and maximum 63.9 %CH_4 was generated between 6 and 30 day's retention time from SW and SHW respectively (Figure 4.3(a)). This temperature level was observed to have relatively high retention time and lower %CH_4 because enzymatic activity of the bacteria largely depends upon temperature, which is critical factor for CH_4 production is low at low temperatures cause them to become dormant (BSP-Nepal, 2005).

From the experimental result, digesters at 37°C were generating biogas with maximum %CH_4 composition. At this temperature level 56, 73.2, 58.6 and 77.8 %CH_4 biogas was produced from SW, SHW, FVW and M at 20, 22, 24 and 20 days of retention time respectively as shown in the Figure 4.3(b). Literatures were indicating that mesophilic micro-organisms grow best at this temperature (BSP-Nepal, 2005; Culhane, 2012). This is verifying fact that most biogas processes is generally run at 37°C.





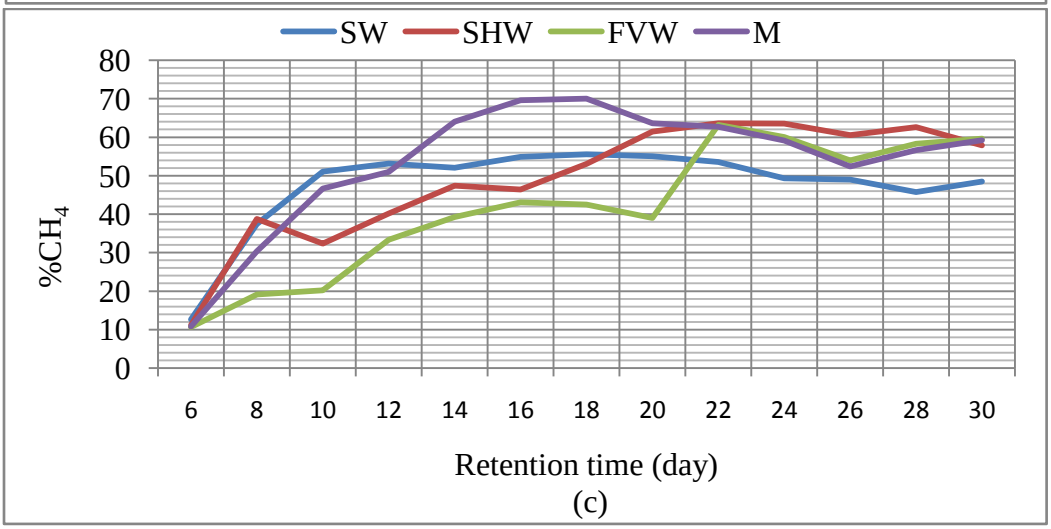


Figure 4.3: %CH_4 versus retention time in days at (a) room temperature, (b) 37°C, (c) 45°C

At 45°C experimental anaerobic digesters working temperature 55.5, 63.6, 63.2, and 70.0 $\%CH_4$ was produced from SW, SHW, FVW, and M between 18 and 22 retention times as indicated in the Figure 4.3(c). Though this temperature level generates more biogas, its $\%CH_4$ is less when compared to $\%CH_4$ value of biogas produced at 37°C irrespective of waste types because this temperature is favorable for methanogenesis bacteria.

As indicated by the above graphs at each temperature levels, $\%CH_4$ in the biogas increase until it reach optimum point. Buysman, (2009) and Thibault, (2010) pointed out that as retention time increases; all the microbes have sufficient time to degrade the substrate and to have a net growth rate. Then, the bacteria will starve and the production of CH_4 decreases once the optimum is exceeded.

Anaerobic digestion of M was produces high $\%CH_4$ biogas at the three temperature levels. In contrast, FVW was examined to generate low $\%CH_4$ biogas due to VFAs inhibition. For FVW, $\%CH_4$ biogas versus retention time curve line (green color) keeps on increasing and this indicate that organic matter in this waste was partially digested.

4.2.3. Methane Yield

To determine CH_4 yield on the anaerobic digestion during the given retention time, change in the VS on digestion was analyzed before digestate disposal and summarized in Table 4.2.

Table 4.2: Percent VS of digestate after 30 days of anaerobic digestion

Waste Type	%VS		
	Temperature		
	Room Temperature	37°C	45°C
SW	29.5	21	19.3
SHW	43	25.6	18.75
FVW	40	38	17.7
M	29.6	23.55	19.14

Using the change VS value of fed and digestate CH_4 yield was calculated using Equation (3.10). Full calculation summary of CH_4 yield is given under Appendix C. Methane yield is more useful than biogas yield if an accurate CO_2 or CH_4 detector like gas analyzer is available. Methane yields of 0.12 and 0.16 l CH_4/gVS for SHW and M at 37°C and 0.092 and 0.13 l CH_4/gVS for FVW and SW was achieved experimentally at 45°C. An earlier pilot scale study reported yields

of 0.16 and 0.19 liter CH4/g VS with retention times of 21 and 42 days respectively (California Integrated Waste Management Board, 2008). Despite for FVW, the results presented in this paper for SW, SHW and M were therefore relatively comparable with these earlier results (as shown in Figure 4.4 and Appendix C).

In case of SHW and M, maximum CH_4 yield was observed at 37°C. This study shows that FVW digestion alone results in low biogas production and CH_4 yield despite its high biodegradability due to VFAs inhibition.

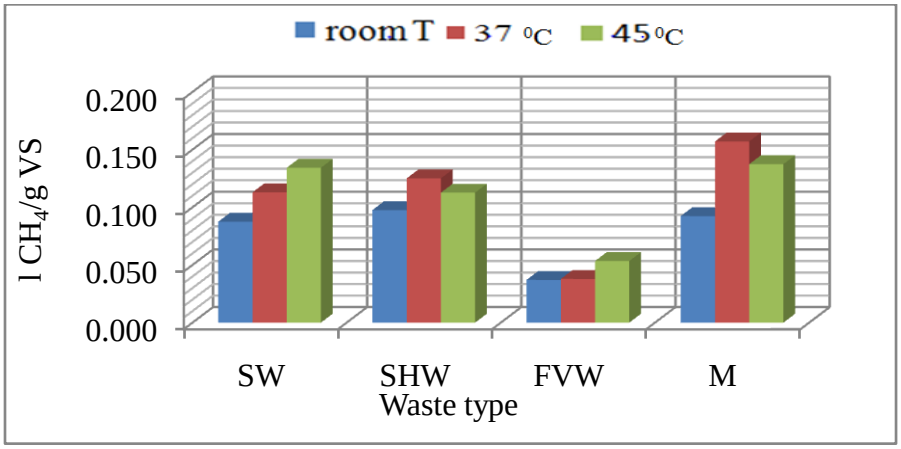
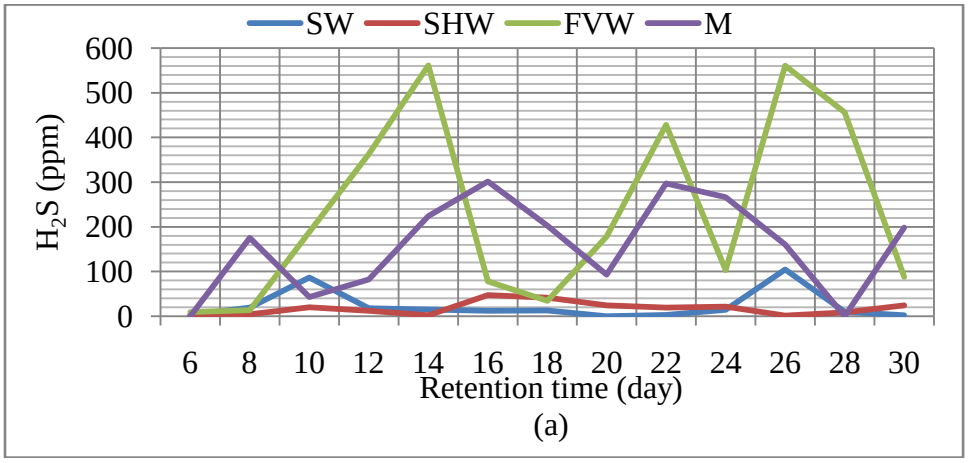


Figure 4.4: Methane yield (l CH_4/g VS)

4.2.4. H_2S

More H_2S production was observed at temperature of 45°C. This is because of unbalanced fermentation could occur due to prolonged exposure to this temperatures, thus favoring the sulphur-reducing bacteria, resulting in the formation of more H_2S (Sue, et al., 2009).



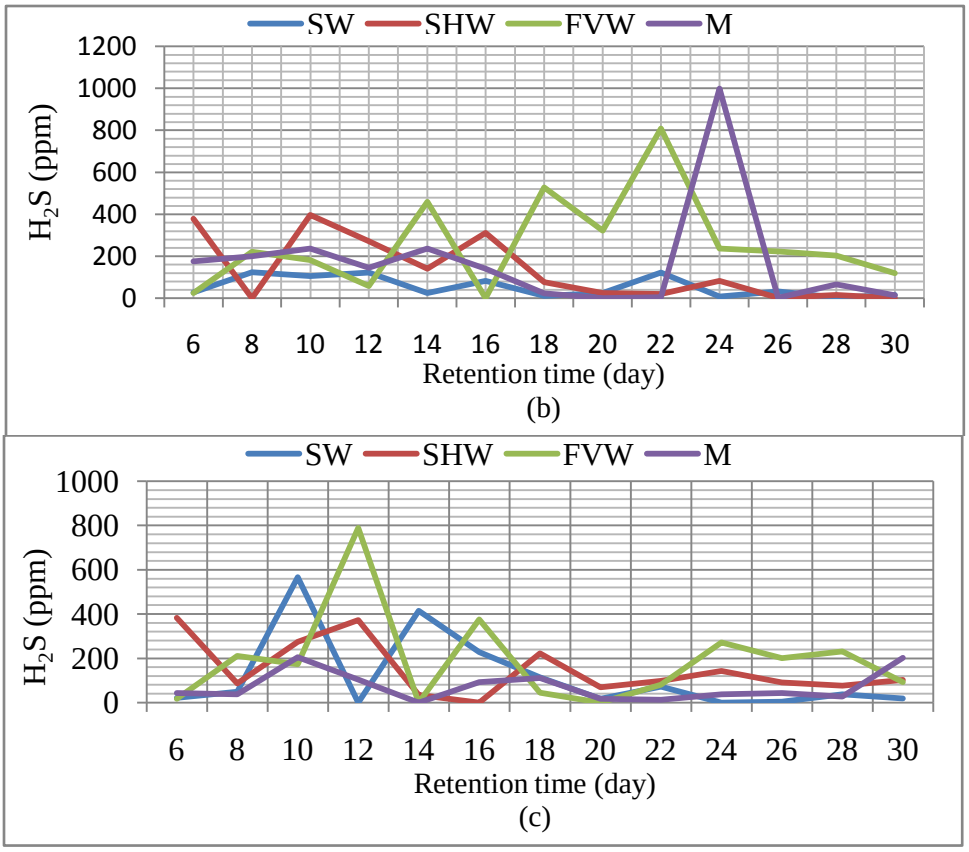


Figure 4.5: H_2S composition of biogas produced at (a) room temperature, (b) 37°C (c) 45°C

Fruit-vegetable waste was observed to generate 3059, 4382, and 4491 in ppm H_2S and these values are relatively more compared to others (as shown in the Figure 4.6 and Appendix E). Fruit-vegetable wastes used in this study contain significant amount cabbage which rapidly spoiled at fruit-vegetables market. According to Asquer, et al. (2013) report on characterization of FVWs as a single substrate for the anaerobic digestion, cabbage was indicated to contain more sulfur.

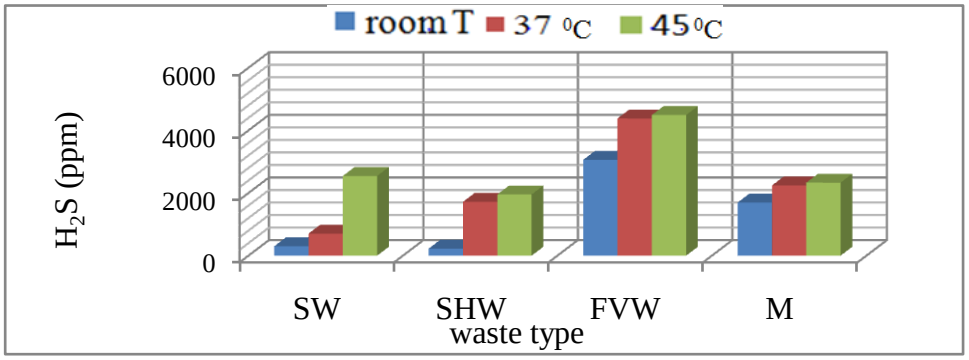


Figure 4.6: Total H_2S production in ppm of anaerobic digestion

4.3. Experimental Results Data Analysis

4.3.1. Analysis of variance (ANOVA)

Experimental result data analysis model annotated view was labeled as "significant." This is arbitrarily based on Design-Expert program's default for a significance threshold of probability > F value 0.05. The Model F-value of 5.85 and 21.49 imply that the models were significant. There is only a 1.58% and less than 0.01% chance that a 'Model F-Value' could occur due to noise for both biogas generation and $\%CH_4$ composition, respectively.

Table 4.3: ANOVA experimental results data analysis summary using design expert 6.0.8

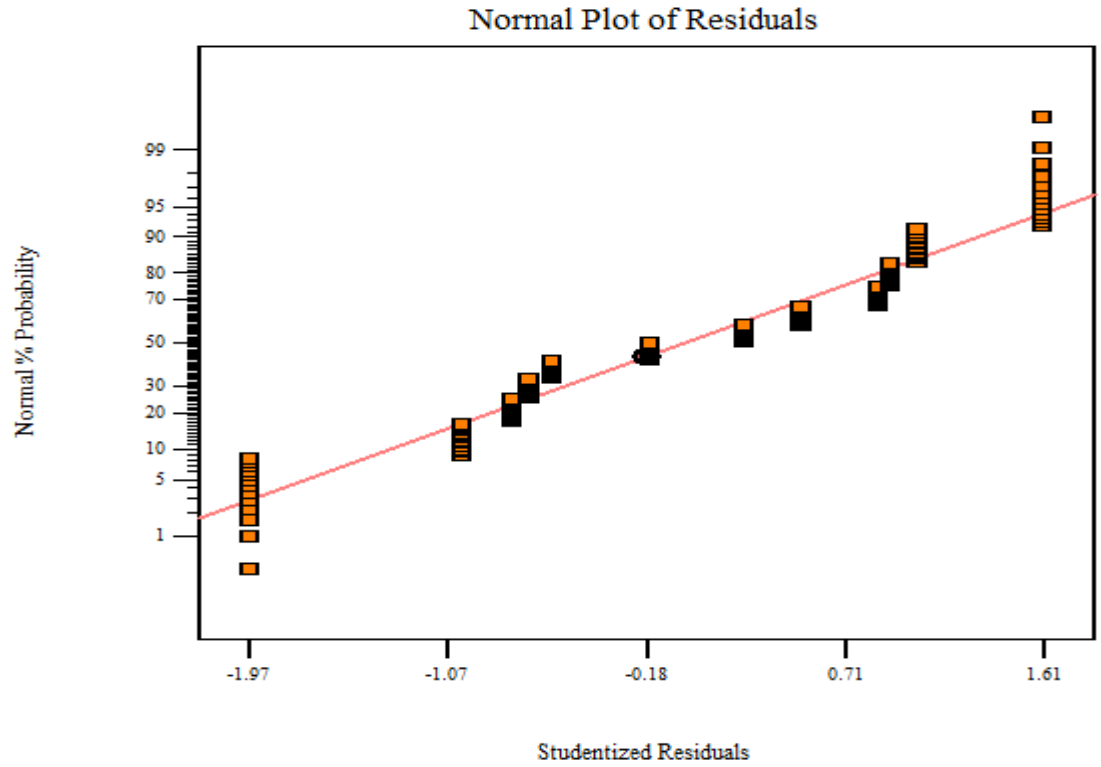
Response: Biogas						
Source	Sums of squeres	DF	Mean squere	F value	Prob> F	
Model	23.63	149	0.16	5.85	0.0158	significant
A	2.20	2	1.10	40.67	0.0003	
B	2.68	12	0.22	8.24	0.0084	
C	3.18	3	1.06	39.16	0.0002	
AB	3.68	24	0.15	5.65	0.0195	
BC	4.85	36	0.13	4.97	0.0258	
ABC	7.04	72	0.098	3.61	0.0540	
Response: CH_4						
Model	52918.04	83	637.57	21.49	< 0.0001	significant
A	4444.93	2	2222.46	74.91	< 0.0001	
B	30792.18	12	2566.01	86.49	< 0.0001	
C	9250.51	3	3083.50	103.93	< 0.0001	
AB	1728.22	24	72.01	2.43	0.0021	
AC	2731.78	6	455.30	15.35	< 0.0001	
BC	3970.42	36	110.29	3.72	< 0.0001	

Values of 'probability > F' less than 0.05 indicate model terms were significant. As indicated in Table 4.3, temperature (coded 'A'), retention time (coded 'B'), waste type (coded 'C'), interactions of temperature - retention time (coded 'AB'), and retention time - waste type (coded 'BC') were significant model terms for both biogas product and $\%CH_4$ compositions.

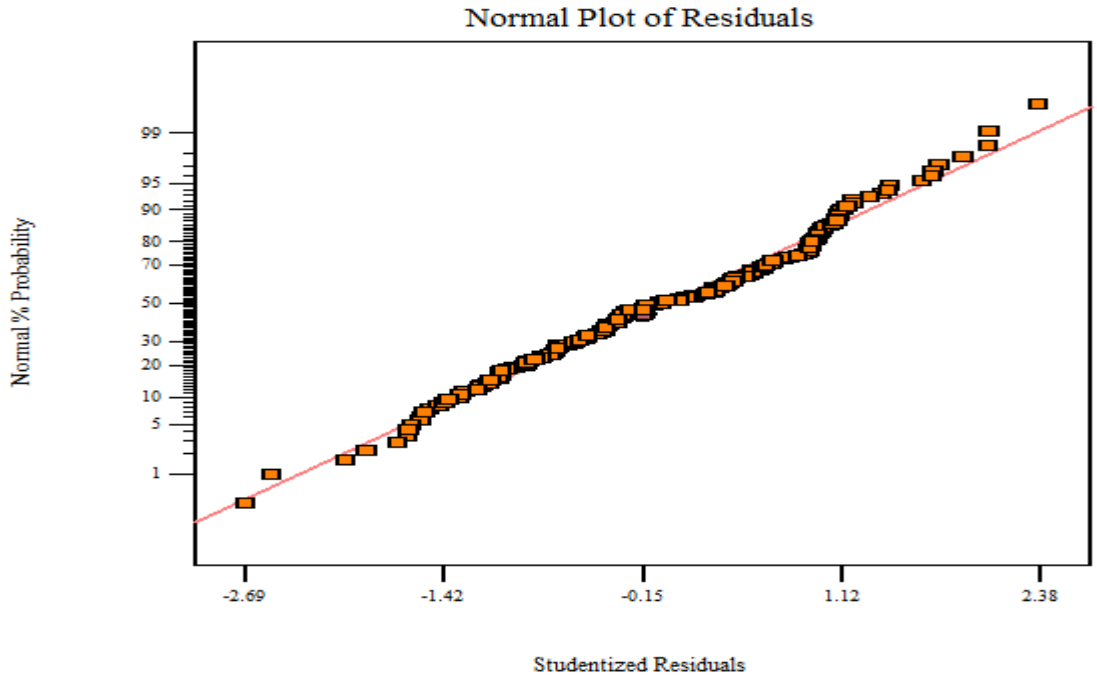
4.3.2. Diagnostics plot

The adequacy of the experimental data were analyzed using normal plot of residuals, residuals versus predicted and outlierT graphs for biogas product and $\%CH_4$ responses. Normal plot of residuals graph is a technique for assessing whether or not a data set is approximately normally distributed. The experimental data were plotted against a theoretical normal distribution in such a

way that points should form approximate straight-line. Normal plot of residuals graph for biogas product and %CH_4 responses is given Figure 4.7(a) and (b), respectively.



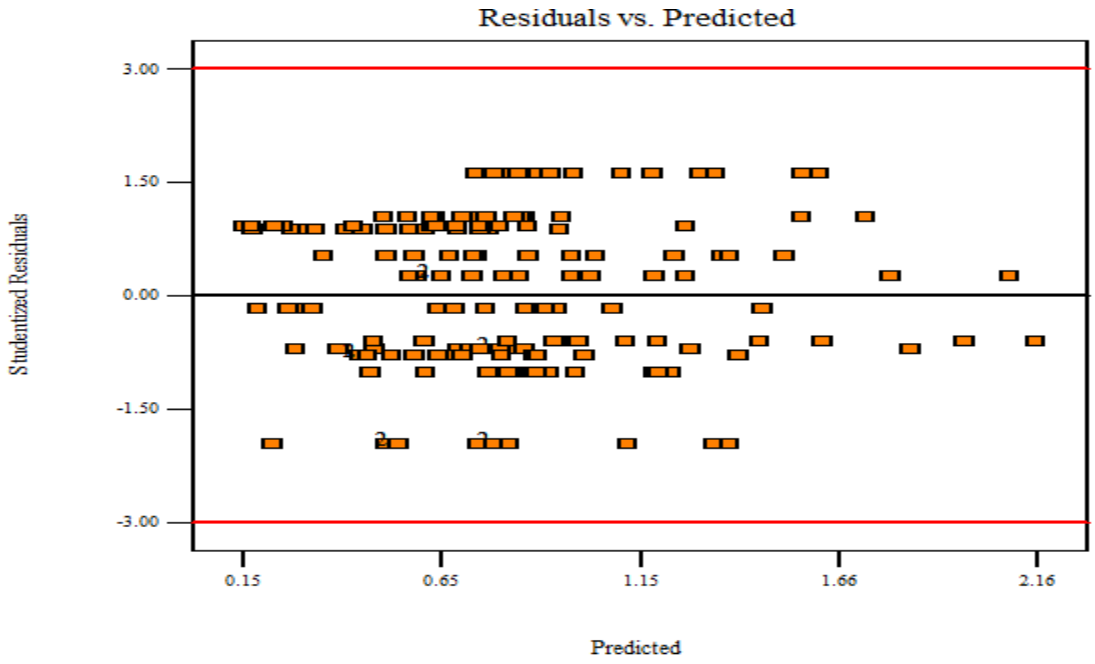
(a)



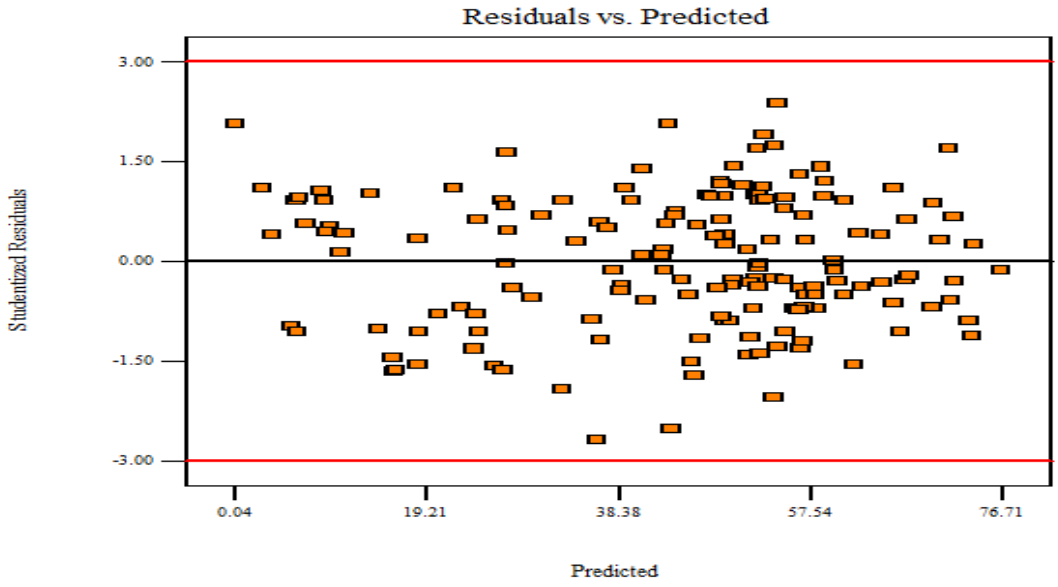
(b)

Figure 4.7: Normal plot of residuals graph (a) biogas product and (b) %CH_4

Running a regression analysis, the variance of the error terms must be constant and they must have a mean of zero. If this is not the case, the model may not be valid. The points on the plot appear to be randomly scattered around zero so assuming that error terms had a mean of zero was reasonable. The vertical width of the scatter does not appear to increase or decrease across the fitted values. Figure 4.8 (a) and (b) indicated that the variance in the error terms of biogas product and $\%CH_4$, respectively were constant.



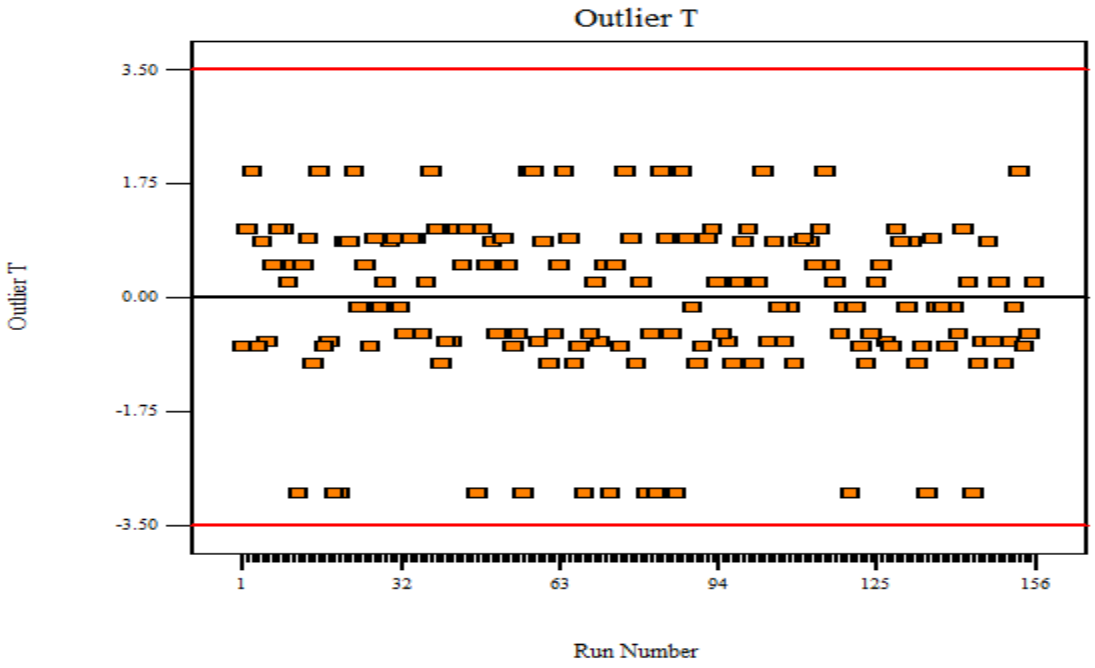
(a)



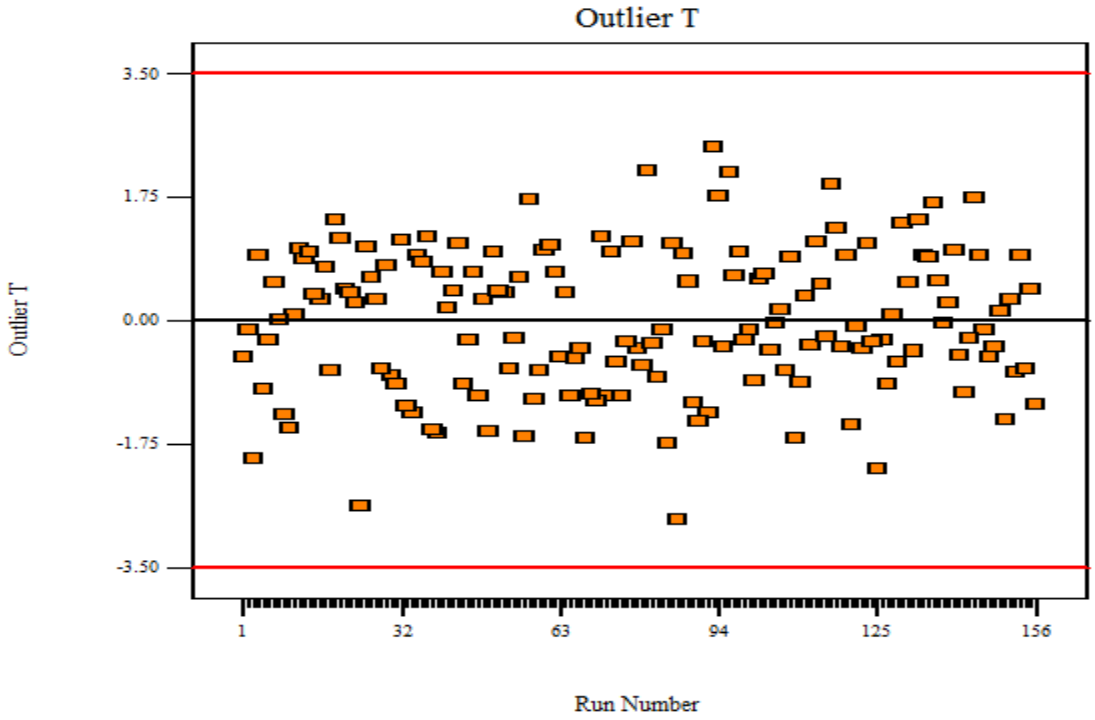
(b)

Figure 4.8: Residuals versus predicted graph (a) biogas product and (b) $\%CH_4$

An outlierT is an observation point that is distant from other observations. An outlierT is due to variability in the measurement or it is indicate experimental error. An outlierT for biogas product and $\%CH_4$ indicated no excluded data sets or measurement errors (Figure 4.9(a) (b)).



(a)



(b)

Figure 4.9: An outlierT graph (a) biogas product and (b) $\%CH_4$

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Sewage, slaughterhouse, fruit-vegetable wastes and their mixture were analyzed in terms of total solids, volatile solids, biochemical oxygen demand, chemical oxygen demand, pH, total nitrogen and C: N ratio. Total volatile solids (as %TS) value of 74.54%, 87.46% and 88.59% for SW, SHW, and FVW, respectively indicated that these wastes have potential for biogas production under anaerobic digestion. Furthermore, differences in their C: N ratio showed that they are complimentary to each other and then co-digestion can result in optimum biogas production. The fact, which is supported by higher $\%CH_4$ biogas observed for mixture of aforementioned wastes rather than individual waste.

From the laboratory investigation, it can be concluded that SW produced relatively low in amount and $\%CH_4$ biogas composition irrespective of digestion temperatures. Despite, its low C: N ratio, SHW was observed to produce maximum of 61.3, 63.6, and 73.2 $\%CH_4$ at room temperature, 45°C and 37°C anaerobic digestion temperatures correspondingly and this is due to ammonia adaptation of methanogens.

In spite of high biodegradable organic matter content of FVW, anaerobic digestion of this waste was observed to generate 51.8, 58.6, and 63.2 $\%CH_4$ at room, 37°C, and 45°C temperature, respectively. A decrease in pH recorded in anaerobic digesters of this waste due to accumulation of VFAs.

This study showed that biogas production increases with temperature irrespective of waste types. Comparatively, mixture of SW, SHW, and FVWs observed generate high biogas than individual wastes. Moreover, this study showed that $\%CH_4$ in the biogas increased with retention time until it reached optimum point and decreased afterwards as the micro-organisms starved due to lack of sufficient food from the waste in the anaerobic digesters. It was concluded that anaerobic digestion at optimum retention time, could optimize $\%CH_4$ in the biogas product.

Minimum and maximum CH_4 yield resulted from FVW and M, respectively. In case of SW and FVW, CH_4 yield increased with temperature. Maximum methane yield of 0.12 and 0.16 liter CH_4 per gVS digestion resulted at 37°C for SHW and M, respectively. Based on this co-digestion of sewage, slaughterhouse and fruit-vegetable concluded to generate high biogas

product and methane yield. The results of the product characterization using gas analyzer demonstrated that H_2S rate has increased with temperature irrespective of the waste types. Comparatively, high H_2S observed for FVW due to significant amount of cabbage composition of FVW, which rapidly spoiled at fruit-vegetables market.

5.2. Recommendations

Based on this thesis work, the following recommendations are suggested for future research which is related to biogas production potential of SW, SHW, FVW and co-digestion of their mixtures:

- From the experimental investigation utmost $\%CH_4$ biogas observed from co-digestion of wastes. Thus, further research on their co-digestion will be recommended.
- Disposal of SW, SHW, FVW and co-digestion of their mixture needs consideration to generate energy from it and to make clean environment, assure sustainable and green economy.

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Appendixes

Appendix A: Sample Characterization: Total Solids and Volatile Solids Data Sheet

After overnight drying sample at 103°C to get constant mass and cooling in desiccator				
Weights (g)	Waste types			
	SW	SHW	FVW	M
W_{DC}	22.93	23.28	21.94	20.70
$W_{DC} + W_{WS}$	47.46	47.40	31.94	44.06
$W_{WS} = (W_{DC} + W_{WS}) - W_{DC}$	24.53	24.12	10.00	23.36
$W_{DC} + W_{DS}$	24.01	24.70	28.74	22.16
$W_{DS} = (W_{DC} + W_{DS}) - W_{DC}$	1.09	1.42	3.2	1.46
$\%TS = \frac{W_{DS}}{W_{WS}} x100$	4.44	5.89	32	6.25
VS at 550°C				
W_{DC} + ash	23.12	23.44	22.19	20.90
Ash =(W_{DC} + ash) - W_{DC}	0.28	0.18	0.37	0.24
$W_{VS} = W_{DS}$ - Ash	0.81	1.24	2.83	1.22
$\%VS = \frac{W_{VS}}{W_{DS}} x100$	74.54	87.46	88.59	83.61

%TS	percent of total solids
%VS	percent of volatile solids
FVW	Fruit-Vegetable Waste
M	Mixture
SHW	Slaughterhouse Waste
SW	Sewage Waste
V_{WS}	Volume of wet sample
W_{DC}	Weight of dry crucible
W_{DS}	Weight of dry sample
W_{VS}	Weight of volatile solids
W_{WS}	Weight of wet sample

Appendix B: Experimental anaerobic digester results

Day	Sewage Waste: Temperature –Room					
	Biogas (l)	%CH_4	%CO_2	%O_2	H_2S(ppm)	%Balance
6	0.20	2.1	42.8	2.2	3	53.4
8	0.80	17.5	36.5	1.7	19	36.9
10	0.64	29	28.4	9.1	86	40.1
12	0.44	27	21.7	2.5	18	48.9
14	0.48	37.4	20.9	2.4	15	40.3
16	0.78	32.5	22.6	1.4	12	42.2
18	0.98	43.7	19.3	2.7	13	35.4
20	0.34	43.5	21.7	1.6	0	33.5
22	0.72	37.1	22	1.3	3	37.3
24	0.60	45.9	18.3	3.6	14	31.9
26	0.54	51.0	33.9	3.9	104	12
28	0.36	52.7	27.0	3.1	10	18.5
30	0.30	50.6	29.8	1.8	2	19.6
T= 37°C						
6	0.64	11.5	51.9	3.6	27	33
8	1.46	36.2	38.7	2.4	124	22.7
10	0.88	34.4	24.3	1.9	106	39.4
12	0.94	42.3	38.2	2.9	123	16.6
14	1.08	43.6	33	1.2	25	22.2
16	0.91	45.3	33.3	3.3	83	18.1
18	0.76	55.8	31.3	2.7	10	10.2
20	0.68	56.0	29.0	2.4	25	12.6
22	0.86	55.0	27.9	3	123	14.1
24	0.28	54.5	23.7	4.3	8	17.5
26	0.32	53.7	28.1	2.7	32	15.5
28	0.26	52.1	23.9	2.3	3	21.7
30	0.18	52.4	25.3	3.3	15	19
T=45°C						
6	0.82	12.6	52.7	4.6	22	30.1
8	0.67	37.4	46.3	3.6	49	12.7
10	0.74	51	31.1	2.1	567	15.8
12	1.82	53.1	27.9	3	>>>	16
14	1.26	52	29	2.4	415	16.6
16	0.84	54.8	32.7	2.3	228	10.2
18	0.70	55.5	31.3	2.7	114	10.5
20	0.78	55.0	25.3	5	17	14.7
22	0.78	53.5	26.8	2.7	73	17
24	0.73	49.3	21.3	1.5	0	27.9
26	0.46	48.9	23	3.1	5	25
28	0.37	45.7	24.6	2.8	37	26.9
30	0.26	48.4	22.3	2.3	19	27

Appendix B: Experimental anaerobic digester results, continued

Day	Slaughterhouse Waste: Temperature –Room					
	Biogas (l)	%CH_4	%CO_2	%O_2	H_2S(ppm)	%Balance
6	0.86	12.4	52	3.4	2	32.2
8	0.78	20.2	44.7	1.6	4	33.5
10	0.64	26.6	38	2.9	20	32.5
12	0.42	26.4	34.1	1.8	12	37.7
14	0.68	43	26.2	1.5	2	29.3
16	0.44	43.2	29.3	2.2	47	25.3
18	0.50	47	29.4	3.3	41	20.3
20	0.44	50.1	29.8	1.6	24	18.5
22	1.38	51.3	28.3	2.4	19	18
24	0.99	50.5	28.1	2.8	21	18.6
26	0.87	51.2	24.6	2.2	1	22
28	0.62	61.3	24.5	1.2	8	13
30	0.56	56.2	27.9	2.6	24	13.3
T= 37°C						
6	0.76	14.5	59.5	4.2	379	21.8
8	0.89	41.1	23.3	3.1	>>>	32.5
10	1.38	48.4	21.3	3.4	397	26.9
12	1.4	60	21.6	2.5	272	15.9
14	1.26	56.4	20	4.1	140	19.5
16	1.54	57	25	2.8	312	15.2
18	1	55.3	23.7	3.9	77	17.1
20	0.69	56.2	28	2.6	24	13.2
22	1.06	73.2	22.6	3.0	20	1.2
24	0.75	70.2	22.6	2.4	83	4.8
26	0.53	67.3	23	1.5	1	8.2
28	0.6	69.5	26.3	2.8	15	1.4
30	0.37	66	26.3	1.8	0	5.9
T=45°C						
6	0.6	11.1	56.6	1.9	383	30.4
8	0.82	38.7	31.8	5.5	86	24
10	0.74	32.3	33	3.9	275	30.8
12	0.66	40.1	36.1	3	373	20.8
14	0.58	47.4	32.8	3.5	35	16.3
16	1.8	46.4	30.7	2.8	>>>	20.1
18	2.1	53	25.5	2	223	19.5
20	1.28	61.4	28.6	1.2	69	8.8
22	1.2	63.6	23.9	1.6	98	10.9
24	0.99	63.5	26.5	2.8	143	7.2
26	1.04	60.5	24.4	2.5	91	12.6
28	0.86	62.6	28.5	1.8	76	7.1
30	0.66	57.9	25.6	2.0	103	14.5

Appendix B: Experimental anaerobic digester results, continued

Day	Fruit-Vegetable Waste: Temperature –Room					
	Biogas (l)	%CH_4	%CO_2	%O_2	H_2S(ppm)	%Balance
6	0.72	2.3	60.1	15.6	9	22
8	0.8	5.2	47.6	7.5	13	39.7
10	0.83	9.2	41.7	4.2	188	44.9
12	0.66	10	56.2	3.1	363	30.7
14	0.28	26	63.2	2.3	561	8.5
16	0.78	19.6	40.5	3.1	78	36.8
18	0.67	30.2	33.8	3.8	34	32.2
20	0.46	33.3	31.9	3.2	178	31.6
22	0.26	35.3	21.2	5.5	428	38
24	0.18	39.7	29.6	2.2	103	28.5
26	0.2	46.3	23.1	2.7	560	27.9
28	0.9	49.6	19.6	5.3	456	25.5
30	1.3	51.8	11.5	7.4	88	29.3
T= 37°C						
6	1.28	7.7	57.6	4.8	25	29.9
8	1.06	9.5	42.7	6.4	221	41.4
10	0.74	17.3	40.5	1.5	181	40.7
12	0.74	9.8	54.6	13	58	22.6
14	0.16	10.1	53.7	3.8	459	32.4
16	1.32	10.4	55.3	4.5	>>>	29.8
18	0.46	21.2	38.2	6.5	528	34.1
20	0.48	20.5	40.4	3.5	321	35.6
22	0.45	26.3	46.4	4.3	808	23
24	0.48	58.6	33.3	2.2	236	5.9
26	0.76	53.0	25.5	2.0	223	19.5
28	0.72	51.3	24.6	2.4	203	21.7
30	0.68	55.3	31.5	3.4	119	9.8
T=45°C						
6	1.6	10.6	59.3	5.8	18	24.3
8	0.9	19.1	41	5.1	211	34.8
10	0.78	20.2	45.5	3.9	174	30.4
12	1.76	33.3	39.2	3	789	24.5
14	0.67	39.2	32.3	3.5	>>>	25
16	0.8	43.1	45.8	2.1	376	9
18	0.89	42.5	29.1	1.9	45	26.5
20	0.66	39	26.4	2	>>>	32.6
22	0.6	63.2	24	2.7	81	10.1
24	0.99	60.0	21.6	2.5	272	15.9
26	0.54	54	24.5	3.1	201	18.4
28	0.74	58.3	22	2.6	231	17.1
30	0.87	59.6	29.3	2.3	93	8.8

Appendix B: Experimental anaerobic digester results, continued

Day	Mixture: Temperature –Room					
	Biogas (l)	%CH_4	%CO_2	%O_2	H_2S(ppm)	%Balance
6	0.78	6.8	52.7	3.6	0	36.9
8	0.96	12.6	24.3	1.2	175	61.9
10	0.8	20.8	20.6	3.1	43	55.5
12	0.85	27.7	21.8	3.3	82	47.2
14	0.74	45.6	30.2	4	224	20.2
16	0.58	46.8	31	3.2	301	19
18	0.44	46.2	30.3	4.9	202	18.6
20	0.89	47.4	25.7	2.5	93	24.4
22	1.16	49.5	24.1	0.8	297	25.6
24	1.2	51.1	31.9	3.1	266	13.9
26	1.17	56.6	31.4	3.5	160	8.5
28	0.86	59.5	13.4	4.3	0	22.8
30	0.79	63.9	30.4	2.4	198	3.3
T= 37°C						
6	1.36	12.6	54.3	3.2	175	29.9
8	1.66	25.7	42.8	4.2	200	27.3
10	0.88	58.6	33.3	2.2	236	5.9
12	1.62	64.4	28.8	3.7	145	3.1
14	0.79	66.2	28.9	2	237	2.9
16	1.4	66.7	29	2.1	141	2.2
18	1.04	71.7	21.7	1.1	23	5.5
20	0.9	77.8	20.7	0.3	0	1.2
22	0.84	74.4	25.1	1.2	5	0
24	0.95	76.2	23.1	1	1000	0
26	1.24	75.0	6.0	0.8	1	18.2
28	1.16	70.9	20.1	3.5	65	5.5
30	0.98	69.6	22.4	2.7	14	5.3
T=45°C						
6	0.8	10.8	50.6	3.1	43	35.5
8	1.6	30.3	46.6	4	38	19.1
10	1.18	46.6	35.3	4.4	205	13.7
12	0.96	51	33.9	3.9	104	11.2
14	1.44	64	30.5	2.4	>>>	3.1
16	1.1	69.6	25.1	2.1	92	3.2
18	1.96	70.0	27.9	2.6	111	-0.5
20	2.14	63.6	25.7	2.2	17	8.5
22	0.97	62.7	23.9	3.9	13	9.5
24	0.92	59.1	25	1.9	37	14
26	0.98	52.4	28	1.1	43	18.5
28	0.59	56.6	31.4	2.5	27	9.5
30	0.46	59.2	30.3	4.9	202	35.5

Appendix C: Methane yield calculation summary

Waste Type	Temperature	VS_f (as %TS)	%TS	VS_i	VS change $= VS_i - VS_f$	TS =1500x%TS	gVS =TS x %VS change	CH_4 (l)*	Yield (l CH_4/gVS)
SW	Room T	29.5	4.43	74.54	45.04	66.45	29.93	2.62	0.087
	37 °C	21	4.43	74.54	53.54	66.45	35.58	4.02	0.113
	45 °C	19.3	4.43	74.54	55.24	66.45	36.71	4.93	0.134
SHW	Room T	43	5.89	87.46	44.46	88.35	39.28	3.83	0.097
	37 °C	25.6	5.89	87.46	61.86	88.35	54.65	6.83	0.125
	45 °C	18.7	5.89	87.46	68.71	88.35	60.70	6.84	0.113
FVW	Room T	40.3	8	88.59	48.59	120	58.31	2.16	0.037
	37 °C	38	8	88.59	50.59	120	60.71	2.30	0.038
	45 °C	17.7	8	88.59	70.89	120	85.07	4.54	0.053
M	Room T	29.6	6.25	83.61	54.01	93.75	50.63	4.68	0.092
	37 °C	23.55	6.25	83.61	60.06	93.75	56.31	8.84	0.157
	45 °C	19.14	6.25	83.61	64.47	93.75	60.44	8.30	0.137

***** Represent sums of each run biogas production in Liter multiplied by its corresponding $\%CH_4$ composition.

$\sum_{i=6}^{n=30} Bg_i \times \%CH_{4i}$

Bg_i - biogas produced from each run

Appendix D: Sums of biogas produced within 30 days retention time

	Biogas (l)		
Waste type	Room Temperature	37°C	45°C
SW	7.18	9.25	10.23
SHW	9.18	12.23	13.33
FVW	8.04	9.33	11.8
M	11.22	14.82	15.1

Appendix E: Sums of H_2S produced within 30 days retention time

	H_2S(ppm)		
Waste type	Room Temperature	37°C	45°C
SW	299	704	2546
SHW	225	1720	1955
FVW	3059	4382	4491
M	1697	2242	2332

Declaration

I declare that this thesis entitled "Comparative Study on biogas production potentials of Sewage, Slaughterhouse, Fruit-Vegetable wastes and their co-digestion is my own, original work done under the supervision of Dr.Ing. Zebene Kiflie at Addis Ababa Institute of Technology in 2015/16 academic year for partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering and that I have not previously submitted it entirely or in part for obtaining any qualification at any other university and all references used in this work have been properly cited and accredited.

Alemu Gizaw Wakene …… ……..
Signature Date