INVESTIGATION OF THE EFFECTS OF SUPPLEMENTING A BIODEGRADABLE MUNICIPAL SOLID WASTE ANAEROBIC DIGESTER WITH MAIZE COBS.

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Investigation of the Effects of Supplementing a Biodegradable Municipal Solid Waste Anaerobic Digester with Maize Cobs.

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the University Supervisors:

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DEDICATION

I am grateful to God for the grace to carry out this work. This work is dedicated to my wife Susan and Children Lucy, Ashley and Ryan without whom, I would have not succeeded. May God bless.

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ABBREVIATIONS

AD - Anaerobic Digestion

APHA - American Public Health Association

ASTM - American Standard Test Method

BMP - Biochemical Methane Potential

CHP - Combined Heat and Power

DM - Dry Matter

KARI - Kenya Agricultural Research Institute

MOE - Ministry of Energy

MSW - Municipal Solid Waste

NaOH - Sodium Hydroxide

ODM - Organic Dry Matter

OLR - Organic Loading Rate

SRT - Solid Retention Time

TS - Total Solids

VFA - Volatile Fatty Acids

VS - Volatile Solids

ABSTRACT

A study was carried to determine the effects of supplementing a municipal solid waste (MSW) anaerobic digester with maize cobs. This was an effort aimed at making biodegradable MSW anaerobic digestion more reliable by producing continuous and adequate gas for the intended applications. The study was carried out in a laboratory using protein rich MSW and carbohydrate rich maize cobs in a mesophillic digester for a period of 10 days. The nutrient composition of the feedstock was determined through proximate and ultimate analysis. The results showed varying nutrient composition for maize cobs and municipal solid waste. The co- digestion of MSW and maize cobs resulted in the determination of the optimum mixing ratio for maximum gas yields and quality of gas. The MSW and maize cobs were digested at the ratios of 3:1, 2:1 and 1:1 while the independent digestion of MSW and maize cobs served as the control. It was also noted that the Carbon: Nitrogen(C: N) which is a key component of anaerobic digestion was greatly improved with co-digestion. The comparison of biogas yields from the independent digestion of the feedstock and the yield from co-digestion indicates that, it is beneficial to use a fraction of maize cobs and MSW in an attempt improve the digestion conditions. It was also noted that the composition of final product (biogas) is affected by the type and composition of feedstock. A mixture of MSW and maize cobs at the ratio of 2:1 proved to yield the highest quantity of gas.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Biogas, the gas produced when organic matter of animal or plant ferments in an oxygen-free environment occurs naturally in swamps and spontaneously in landfills containing organic waste. It can also be induced artificially in digestion tanks to treat sludge, industrial organic waste, and farm waste (Igoni *et al*., 2008). Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), with varying amounts of water, hydrogen sulphide (H_2S), oxygen and other compounds. Millions of cubic meters of methane in the form of swamp gas or biogas are produced every year by the decomposition of organic matter, from both animals and plants (Igoni, *et al*., 2008). It is almost identical to the natural gas pumped out of the ground by the oil companies and used by many people for heating houses and cooking. In the past, however, biogas has been treated as a dangerous by-product that must be removed as quickly as possible, instead of being harnessed for any useful purposes. It is only in very recent times that a few people have started to view biogas, in an entirely different light, as a new source of energy for the future.

For Anaerobic Digestion (AD) to be economically viable, a continuous supply of homogeneous feedstock is required, which is not always possible in some regions due to increased demand for waste and varying waste composition. Consequently, there is a need for feedstock supplementation, in order to avoid fluctuations in feedstock composition balance and availability (Lindorfer *et al.*, 2008).

The type and composition of feedstock used in Anaerobic Digestion can greatly affect the stability, performance, and ultimately, the methane productivity of the process. Municipal and industrial waste, rich in lipids and proteins, are attractive as feedstock due to the high methane yields that can be obtained from these materials (Cirne *et al*., 2007). A mixed feedstock is also more likely to be well balanced in terms of the concentration of macro- and micronutrients. However, lipid degradation products (long-chain fatty acids) have been reported to severely inhibit methanogenesis. Also, increasing free ammonia concentration that results from the degradation of proteins has been reported to be inhibitory to aceticlastic methanogens (Schnurer & Nordberg., 2008).

Anaerobic digestion of maize cobs is gaining ground. Maize cobs are dedicated crops cultivated especially for energy production. They can be stored, through the process of ensiling, so that energy can be produced when the demand for, or price of, energy is high. Anaerobic Digestion of maize cobs alone has been plagued by process imbalance, a condition whereby the rate of feedstock hydrolysis and fermentation outweighs methane production through methanogenesis. Poor methane productivity has been reported as a result of low levels of macro and micronutrients (Hinken *et al*., 2008; Pobeheim *et al*., 2010).Nutritional deficiencies, inappropriate amounts of macro and micronutrients, and inadequate alkalinity may result in incomplete, unsTable bioconversion of the feedstock, and may ultimately cause digester failure (Alvarez *et al*., 2010). For the anaerobic digestion process to be productive and sustainable, the concentration of macro and micronutrients such as nitrogen (N), phosphorus (p), sulfur, iron (Fe), nickel (ni), selenium, tungsten, cobalt (Co) and molybdenum, must be within a suiTable range (Demirel & Scherer, 2008; Hinken *et al.*, 2008).

The ratio of Carbon to Nitrogen (C: N) in the feedstock is one of the parameters that have received most attention to date, and a C: N ratio of 16–20 has been suggested for sTable anaerobic digestion processes. These conditions, and suiTable contents of othermacro and micronutrients, can be achieved by the co-digestion of appropriate feedstock (Cavinato *et al*., 2010)

Apart from improving the reliability of feedstock, co-digestion can offer other benefits, such as better cost efficiency, increased biodegradation, dilution of inhibitory compounds, improved nutrient balance, and increased biogas production. Some authors have shown that methaneyield and process performance are improved significantly when maize cobs are co-digested with manure, in contrast to the poor methane yields when crops were digested alone (Angelidaki *et al., 2010*).

The aim of this study was to investigate the potential benefits of municipal solid waste and maize cobs co-digestion. The study was designed based on the operating conditions of a full-scale biogas digester in Ruiru for waste suiTable for anaerobic digestion. The laboratory biogas digester had a feedstock supply of Municipal Solid Waste (MSW) rich in proteins and lipids, varying considerably in amount and composition over the experiment period. The amounts of maize cobs required for the experiment was identified and suitably selected. The main objective was to compare methane yields during operation with recurring variation in composition of feedstock, to operation with maize cobs supplementation. Also the possibility of achieving a good balance between nutrients and carbon source in the feedstock was studied.

1.2 Statement of the Problem

Kenya mainly depends on energy from hydro, geothermal and that of fossil fuels while the energy demand keeps increasing day by day while the supply or generation capacity has not changed much. To satisfy the growing power demand, efforts are being made to supply domestic power needs through biogas digester plants which mostly utilize cattle slurry. With the devolved governments, there is a growing demand for power which has resulted into an interest to generate power from MSW. Anaerobic digestion of MSW has shown varying results of biogas from time to time making it unreliable. The variation has been attributed to the imbalance of biogas production conditions like carbon/nitrogen ratio, temperature of digestion, retention time and digester charge ratio. MSW has been found to possess varying contents of percentage nutrients from time to time which results in an imbalance of anaerobic digestion conditions. It has been noted that MSW is rich in macro and micro nutrients while maize cobs are rich in Organic Dry Matter (ODM) which comprises of larger percentages of volatile solids.

This study sought to analyze the benefits of adding or supplementing MSW digester with maize cobs in the improvement of biogas production.

1.3 Purpose of the Study

This study sought to analyze the effects supplementing MSW digester with maize cobs in the improvement of biogas supply.

It is hoped that the findings will contribute to the understanding of the factors that affect the full exploitation of MSW anaerobic digesters to produce maximum gas. It is also intended that the findings will be used to enhance large scale biogas production from co digestion of municipal solid waste and maize cobs which in turn can be used generate to energy for combined heat and power.

1.4 Research objectives

1.4.1 Main Objective

The main objective of this study was to investigate the effects of MSW and maize cobs co-digestion.

1.4.2 Specific objectives

The specific objectives of the study were:

1. To determine the nutrient composition of feedstock (i.e. Inoculums, MSW and maize cobs).
2. To compare methane yields for digestion of MSW and maize cobs and determine the ratio required for optimum biogas yields.
3. To determine the proportion composition of biogas from MSW, maize cobs and co digestion at various ratios.

1.5 Research Questions

The study was guided by the following questions:

1. What are the nutrient variations in composition of MSW and maize cobs?

2. What ratio of combination of MSW and maize cobs that yields highest quantity of gas?
3. What are the methane yields for MSW and maize cobs digested independently?
4. What is the percentage composition of the biogas from maize cobs and MSW?

1.6 Justification of the study

The power demand in Kenya requires an alternative supply to reduce the load subjected to the national grid. With the potential of power from MSW in urban centers, a substantial load can be supplied. The reliability and consistency of the power system is crucial for the power supply quality. It was necessary that the supply of biogas for Combined Heat and Power (CHP) is predictable to achieve customer satisfaction. This can only be achieved if AD conditions are maintained constant. Currently such conditions keep varying causing the output of biogas to be unpredictable. The study sought to determine whether the addition of maize cobs to the MSW digester would help improve anaerobic digestion conditions for maximum and reliable levels of biogas production.

1.7 Significance of the Study

The study was in response to the increasing power demand and unreliable production of biogas from existing digesters to support generation of power as an alternative to the grid power which has proved to be constrained. The study sought to bring to light the factors that affect biogas production and in particular the composition of MSW and how it can be improved by co-generation with maize cobs.

It is expected that it will also benefit those who produce crops and may not have put the residues to proper use and even create a market for maize cobs. The study also established that there is need to check the composition of feedstock before putting into digesters for optimum biogas generation.

1.8 Scope and delimitations of the Study

The study sought to establish the contribution of maize cobs and MSW to the gross production of biogas. It also determined the best ratio of MSW and maize cobs to realize maximum gas for reliable power supply. The study also went further to determine the proportion of the final product in order to give an indication of the quality of biogas. Therefore the findings are expected to be applicable to all urban centers particularly those located in the vicinity of maize farming areas.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature on the co-digestion of municipal solid waste and maize cobs in Waste-to-energy. The section highlights several cases of municipal waste-to- energy technologies within the globe from a sustainable perspective. The advantages and disadvantages of several waste-to-energy approaches and how gas production may be improved with the addition of maize cobs have also been reviewed.

2.2 Sustainable Waste Management

Solid waste to energy conversion has a close relationship with socio-economic and environmental parameters. The sustainable development in solid waste sector is interconnected with maximum yield from solid waste energy conversion strategies. Nowadays, due to innovative technological development and change in perceptions, solid waste stream is used as an energy recovery resource, which also ensures recovery of natural resources. The production of biogas keeps varying when MSW is digested alone due to variations in organic matter content (Varma, 2009). Dramatic changes in global climate compel the world to use natural resources in a sustainable way and develop technologies for generating waste that ensures sustainability in real sense (Zaman *et al.*, 2009).

2.3 Landfill gas (LFG)

Land fill gas is the product of microbiological decomposition of land filled garbage. The bugs turn samples of organic matter in garbage into methane and carbon dioxide and trace amounts of other compounds. Like biogas landfill gas is composed of approximately 55% methane and 40-45 % carbon dioxide (Tatamiuk, 2007).

Landfills produce landfill gas by the degradation of organic matter under anaerobic conditions**.** The evaluation of any landfill gas recovery project is highly affected by the composition of waste, specifically the organic fraction, moisture level, and the “degradation” factor of different waste components. Landfills with high food waste contents relatively decay faster to generate landfill gas over short period of time (Varma, 2009).

2.4 Anaerobic digestion

Anaerobic digestion is a process where biodegradable material is broken-down through microbes in the absence of oxygen. Special reactors are used for digestion process and controlled specific conditions are provided inside reactors such as pH, moisture content and temperature etc (Lema, 2010). The purpose of these conditions is to provide favorable environment to microbes and allow them to increase their number and to enhance the degradation process to produce methane (Lema, 2010).

Anaerobic digestion facility has the ability to deal with degradable organic fractions of waste streams. Suitable internal system conditions such as warmth and moist are provided for microorganisms to degrade organic waste to stabilize end product, which is free from pathogens and act as a soil conditioner (Varma, 2009). For anaerobic digestion to be effective, quantity of organic components present in solid waste stream has an important value (Tatamiuk, 2007).

The organic fraction may contain yard waste, paper waste, food waste and any other type of organic matter. The anaerobic digestion process is highly successful if the wastes contain high quantities of organic matter. This process produces methane (CH_4) and carbon monoxide (CO) with small fraction of other gas gases such as hydrogen sulphide (H_2S) (Tatamiuk, 2007).

Anaerobic digestion basically consists of three steps. In the first step, organic material is prepared through sorting, segregation and size reduction before being fed into the digester. In the second step, favorable environmental conditions are provided to ensure digestion process through microbes such as pH up to 6.7 and temperature maintained at about 55-60^{0}c centigrade to produce methane. The components are well mixed for approximately 5-10 days, but in colder climate slurry is mixed at low temperature for long time (Pobeheim *et al., 2010*).

In the third step, the residual sludge is disposed of, if it is contaminated, it is treated before it is disposed. The microbes which have vital role in the anaerobic process are classified into two groups: one is the acid forming and second methane (CH_4) forming group. Acid forming group is used to treat complex organic components into simple acids and the methane forming bacterial group converts simple acids into CH_4. The CH_4 forming bacterial group is sensitive to different environmental factors like temperature and amount of oxygen. It is therefore necessary that the temperatures be kept within range and the amount of oxygen controlled. Generation of CH_4 can take place in two ways, either it is collected directly off the landfill sites i.e. bioreactor landfill or sanitary landfill or pre-treated waste digested in digesters (Pobeheim *et al.,* 2010).

The production of biogas from feedstock comprises four phases; hydrolysis, acidogenesis, acetogenesis and methanogenesis as shown in Figure 2.1.The first phase is hydrolysis which is the breaking down of feed stock into smaller constituent parts. The constituent parts or monomers such as sugars are readily available for degradation to other bacteria. Through hydrolysis, the complex organic molecules are broken down into simple sugars, amino acids and fatty acids. The second phase is acedogenesis or fermentation; it is the further breakdown of the remaining components by acidogenic (fermentative) bacteria. This stage creates volatile fatty acids (VFA) along with ammonia, carbon dioxide and hydrogen sulphide. The third phase is acetogenesis where molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, hydrogen and carbon dioxide. The forth and last stage is methanogenesis where intermediate products of the proceeding phase are converted to methane, carbon dioxide and water. These components make up majority of the biogas emitted from anaerobic digestion process or system. Methanogenesis is sensitive to both high and low pH and occurs between pH 6.5 and $_{pH}$ 8.0.The remaining indigestible material which the microbes cannot use and any dead bacteria remains as constitutes the digestate.

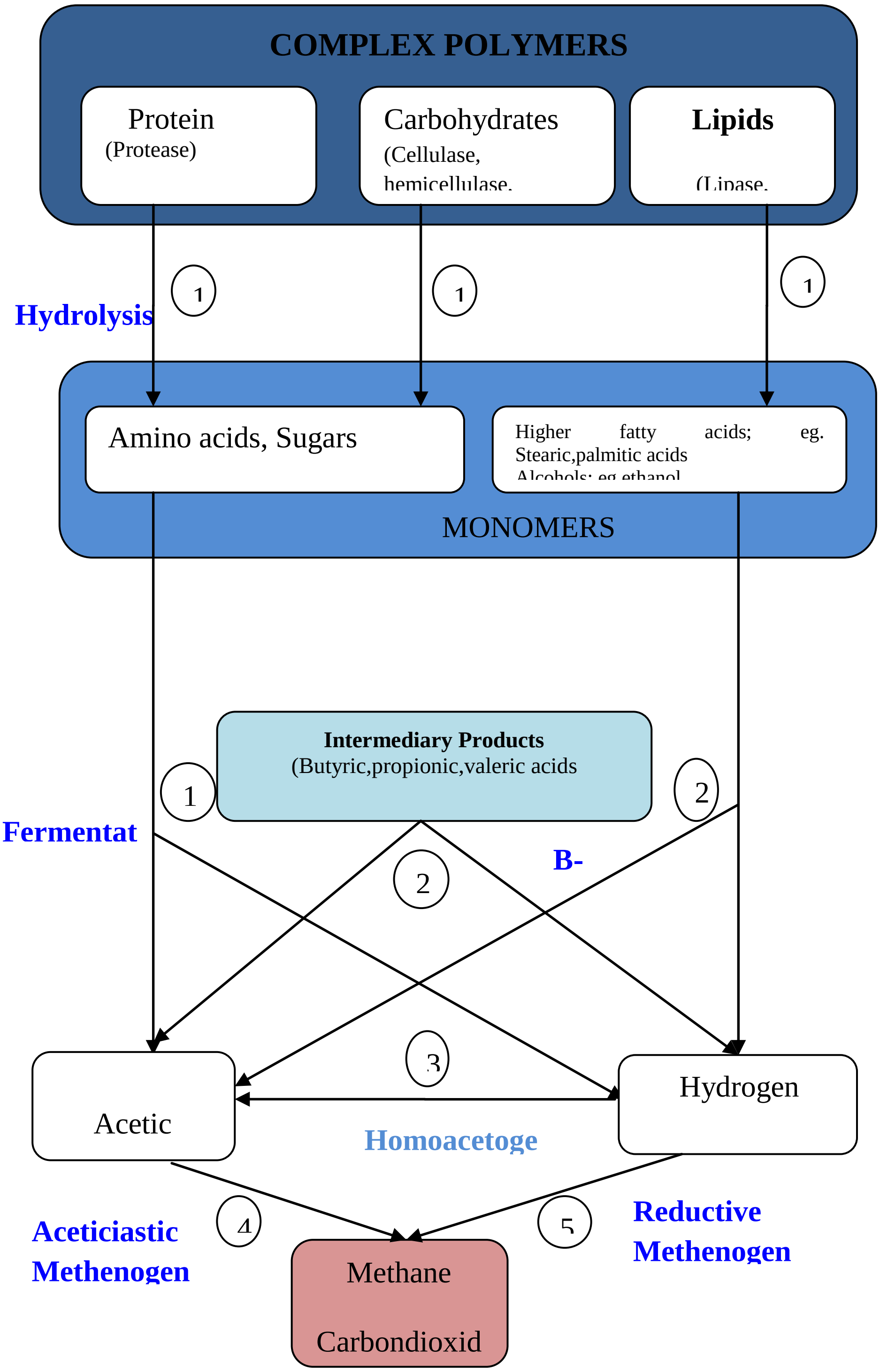

Figure 2.1 Systematic diagram for anaerobic degradation process.

(Murto *et al.*, 2007)

2.4.1 Capital and operational costs

Anaerobic digestion has low capital and operational costs compared to thermal technologies. Surplus energy can be recovered in the form of Methane (CH_4) and also revenue generated through its sale. Pollution control is possible through appropriate control technology. Anaerobic digestion diverts most of organic components from landfills and also reduces risk of gas and leachate production. Well maintained and controlled system ensures low level of environmental pollution (Kapp, 1992). After anaerobic digestion of waste, the waste can be aerobically treated and can get benefits in the form of produced gas and soil conditioner from process for energy production and soil amendment respectively (Tatamiuk, 2007).

2.4.2 Advantages of anaerobic digestion

Anaerobic digestion has some implication in economics and in practical parameters. Anaerobic digestion technology works well on pre-treated waste, like mixing of plastic with organic fraction may cause operational problems. Some anaerobic digestion facilities have ability to deal with mixed solid waste. Bad odor is produced during handling of material. Market value of end product may be lower because of the presence of toxic contaminants in it as it is difficult to get rid of them during processing. Anaerobic digestion has high cost for handling, storage, and processing (Amon *et al*., 2007*)*. Generally this process is used for the sewage and manure treatment because of their homogeneous in nature and also easy for microbes to degrade them. Mixing of these components with solid waste would enhance the microbial activity to degrade it (Tatamiuk, 2007).

2.5 Energy crops used in anaerobic digestion

A number of plants and plant materials have been identified and tested for potential to produce methane. Many varieties of cereals, maize, grass and whole plants have shown good results of methane production. Other crops including hemp, potatoes and flax have tested high amounts of methane. Energy crop residues like maize cobs, rice husks and stalk have also shown potential for methane (Demirel and Scherer 2008; Hinken *et al*., 2008).

Crops are continuously and frequently used for digestion directly after harvest. Time can influence the bio-degradability and hence the methane yield from plants. Late harvesting usually is associated with higher cellulose content in the biomass causing slower bio-degradation and less methane yield. For a year round availability of substrates, the crops are most frequently stored in silage clamps. Under-favorable circumstances, crops can also be dried by using for example surplus heat from Combined Heat and Power CHP (Murto *et al*., 2007; Pakarinen *et al*., 2008)

2.6 Size of biogas unit

The size of a biogas unit depends on several factors (Murto *et al*., 2007) which include the following:

1. The amount and type of organic waste to be disposed in the digester
2. The objective of treating the organic waste (the production of energy and/or organic fertilizer)
3. Demand for biogas and consumption patterns
4. On-site nature of the soil and the level of ground water
5. The training level of the staff on farm and home regarding operation of biogas units

The amount of feedstock fed into a digester each day has an important effect on its performance in terms of digester temperature and retention time. This is measured by volume added in relation to the volume of the digester, but the actual quantity fed to the digester also depends on the temperature at which the digester is maintained. In order to determine the unit size of a biogas unit, the following mathematical equation is used.

Digester size (m^3) = Daily feed-in (m^3/ day) × Retention time (days).

The digester size can be defined as the total size of the biogas unit, which includes the effective size of any volume occupied by the fermented material and the volume of gas storage. Size of the daily feed-in is the size of a mixture of feedstock with water added to the digester once daily or several times and the average concentration of total solids of 10%, where mixing the organic wastes with water depends on its water content. In the case of wet animal wastes, such as manure the proportion of mixing is 1:1 (Florentino, 2003).

In order to plan a biogas plant and to design a digester, several design parameters should be determined which are: ratio of gathered waste from to total waste, number of cattle in farm, amount of manure produced by a cattle which is usually 1.8 m^3/ cattle / month, quantity of daily liquid organic matter deposition into the digester, hydraulic retention time, density and quantity of daily dry organic matter deposition into the digester, and digester load which is usually 2-4 kg m^{-3} day^{-1}. The aforementioned design parameters are used to determine the total volume of the materials that are intended to be stored in the tank and are equal to the internal volume of the tank. Additionally, the designer should take into consideration that a part of the tank (about 10%) is empty and the substrates should not fill it, because it is the place where the gas will accumulate. The same applies in case of designing other storage tanks like liquid organic matter tank (Hansen *et al.*, 1998).

2.7. Types of digesters

During the last century a number of different types of flows in simple digester have been developed and they can be classified as batch flow, continuous flow, continuously expanding, plug flow and contact flow

Conventional digesters are those utilized to process liquid raw materials with a high content in solids, also called rural digesters, the fermentation chamber having a volume below 100 m^3. Conventional digesters are installed without any type of mechanism to reduce the retention time during which the biomass remains inside are predominant; these systems are fed discontinuously and known as discontinuousflow i.e. batch digesters, or fed periodically and known as continuous-flow digesters (Misi and Forster, 2002).

Batch flow digesters are loaded at once, maintained closed for a convenient period, and the organic matter is fermented and then unloaded at a later time. It is quite a simple system with small operational requirements. Installation can be made in an anaerobic tank or in a series of tanks, depending on the biogas demand, the availability and the amount of raw materials to be utilized. Batch flow is most suitable for dry organic matters (solid materials), e.g. solid vegetable waste which are fed into the digester as a single batch. The digester is opened; digestate removed to be used as biofertilizer and the new batch replaces the digestate. The tank is then resealed and ready for operation. Depending on the waste material and the operating temperature, a batch digester will slowly start producing biogas and increase the production with time and then drop-off after 4 to 8 weeks. Batch digesters are therefore best operated in groups, so that at least one digester is always producing biogas (Comino *et al*., 2010)

Continuous flow digesters usually require daily loading and residue management. The process is referred to as continuous since to every daily load corresponds a similar volume load of fermented material. The biomass inside the digester moves through by the difference in hydraulic heat, between the substrate entering the digester and the digestate coming out when unloading. Each load requires a retention time, usually between 14 to 40 days. Continuous digesters can have their retention period reduced by the introduction of agitation and heating. The disadvantage of these models is that the raw material needs to be diluted. The great advantage of these digesters over the batch type is that a single unit allows a continuous supply of biogas and bio fertilizer and the continuous treatment of small amounts of waste (Florentino, 2003). Biogas production can be accelerated by continuously feeding the digester with small amounts of waste daily. If such a continuous feeding system is used, then it is essential to ensure that the digester is large enough to hold all the material that was fed into the digester in the whole digestion cycle.

One key issue is to implement two digesters i.e. accomplishing the biodegradation of the organic waste through two stages, with the main part of the biogas being produced in the first stage and the second stage serving as finishing stage of the digestion at a slower rate. Regarding the continuously expanding flow, the digester starts one third full and then filled in stages and later emptied.

For plug flow digesters, the wastes are added regularly at one end and over-flows at the other. In the contact flow, a support medium is provided. Plug flow can be implemented as continuous biogas digesters in form of fixed dome digester and floating cover biogas digester. The digestion process is the same in both digesters but the gas collection method is different in each. In the In fixed dome the water sealed cover of the digester rises as gas is produced and acts as a storage chamber, whereas the floating cover has a lower gas storage capacity and requires efficient sealing in order to prevent gas leakage. Both have been designed for use with animal waste or dung. Additionally, there are also Philippine and Sri Lankan digesters (Comino *et al*., 2010).

2.7.1 Indian type digester

The Indian-type digester (Figure 2.1) basically is comprises a cylindrical body, gas meter, feed pit and outlet pit (Florentino, 2003). The digester is made using burnt-clay bricks and cement. The cylindrical dome is made of metal sheets and moves up and down as it stores and releases the biogas. The digester is operates continuously and is vertically oriented with a cylindrical shape. The putridity space filled the ground and it has a dividing wall. This dividing wall improves and holds back the fresh slime gush again through short way. The gas is gathered in floating gas lock. The steel gas lock is provided with stir elements. The periodic destruction of swimming layer is performed using the manual stirring of gas lock. The requested gas pressure arises from the heaviness of the swimming gas lock. The gas pressure can basically be changed in the practice by putting things on the gas lock (Comino *et al*., 2010).

This type is suiTable for the homogeneous materials, as for the animals' excrements that do not tend to build sinking layers; the waste must be split. If it is mixed with huge allotments, then it will block the digester. Generally, there are several designs of Indian digesters which include floating gas holder type biogas plant (KVIC model), Deenbandhu model, and Pragati model. The KVIC model is a composite unit of a masonry digester and a metallic dome, where there is maintenance of constant pressure by upward and downward movement of the gas holder. The Deenbandhu model consists of segments of two spheres of different diameters joined at their bases; this model requires lower costs in comparison to KVIC model. The Pragati model is a combination of Deenbandhu and KVIC designs, where the lower part of the digester is semi spherical with conical bottom and the floating drum acts as gas storage (Florentino, 2003).

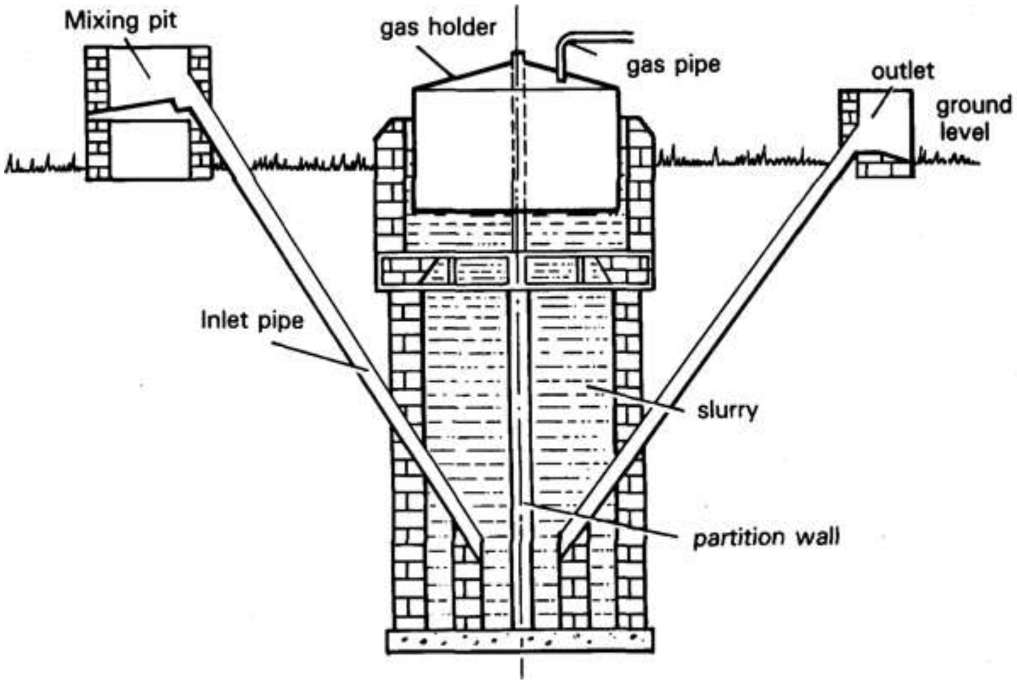

Figure 2.2 Indian-type digester (Florentino, 2003)

2.7.2 Chinese type digester

The Chinese-type model digester (Figure 2.3) is comprised of a cylindrical body, two spherical domes, inlet pit, outlet pit and an inspection opening (Florentino, 2003). The digester is made using cement and bricks and it is a permanent structure. Just as in the Indian digester this has two drains to feed waste and to collect the composted waste.

The biogas is collected in the upper chamber and the waste decomposes in the lower chamber. If the gas pressure exceeds the atmospheric pressure (1 bar) and there is no gas extracted from the dome, then the digestate is squeezed from the reactor into the slurry pipe. If the produced gas is more than the utilized gas, then the slime level will increase. If the utilized gas is more than the produced gas during the gas extraction, then the slime level will sink and the digestate will flow back. The volume of the counterpoise pool must be huge so that the repressed substrate can be digested at the highest gas volume. The gas pressure is not constant in the practice. It increases with the quantity of the stored gas.

Owing to the fact that the biogas dome digesters are completely buried underground, the fermentation temperature should be under a day and night control to maintain a tolerance range from about ± 2 ºC. The difference between summer and winter is large and is subject to the climate zone. The biogas dome digester can be provided with a stir to ensure uniform temperature in the digester. In small family household units, a mixing section for the biogas dome digester is installed before the feedstock is fed to the digester. Different building and construction forms of biogas dome digesters were approved for the Chinese digesters; so that there is a big number of building methods used.

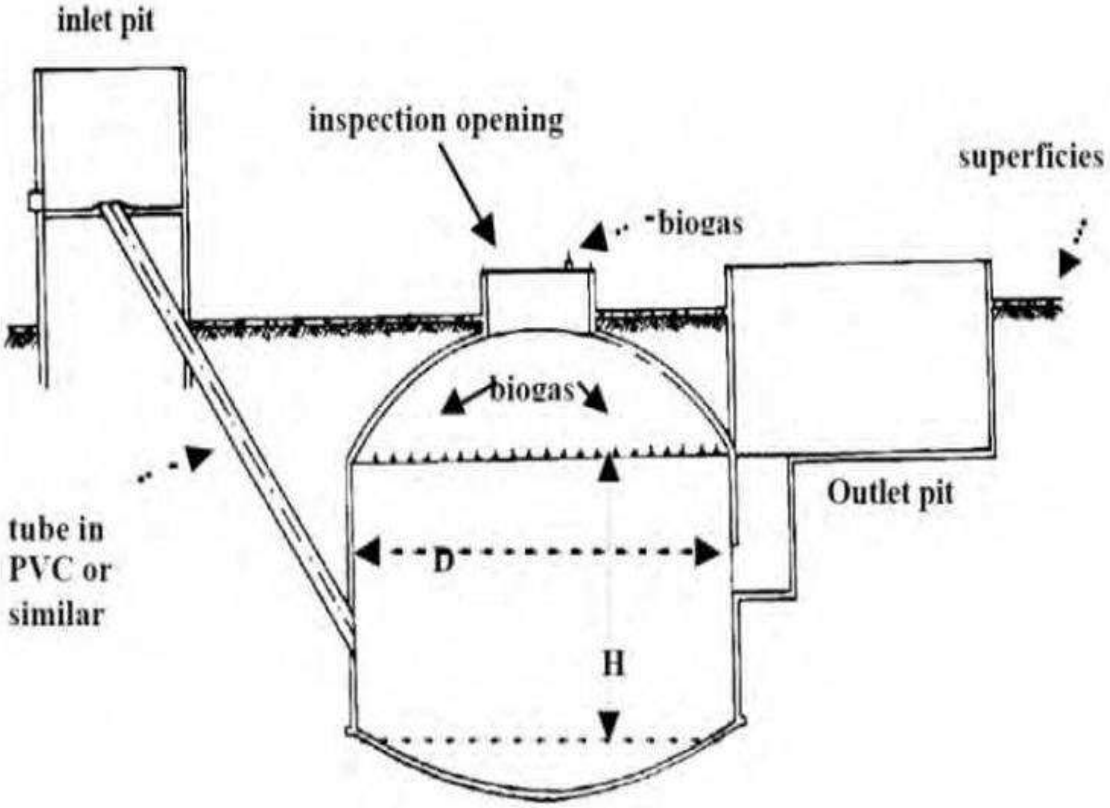

Figure 2.3 Chinese-type digester (Florentino, 2003)

2.8 Designs of Digester

The most common digester design is cylindrical. Digesters can be classified into horizontal and vertical designs. Vertical concrete or steel digesters with rotating propellers or immersion pumps for homogenization are widespread. Vertical tanks simply take feedstock in a pipe on one side, whilst digestate overflows through a pipe on the other side. In horizontal plug-flow systems, a more solid feedstock is used as a plug that flows through a horizontal digester at the rate it is fed-in. Vertical tanks are simpler and cheaper to operate, but the feedstock may not reside in the digester for the optimum period of time. Horizontal tanks are more expensive to build and operate, but the feedstock will neither leave the digester too early nor stay inside the digester for an uneconomically long period (Davidson, 2007)

Anaerobic digesters can be built either above or under the ground. An alternative is that a part of the digester can be buried. Anaerobic digesters constructed above ground have steel structures to withstand the pressure; therefore, it is simpler and cheaper to build the digester underground than having it the surface where mechanical protection is a challenge. Maintenance is, however, much simpler for digesters built above ground and a black coating will help provide some solar heating.

2.9 Co- digestion

Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. In the past anaerobic digestion was a single substrate single purpose treatment until recently when it was realized that anaerobic digestion can become better and more stable when two or more substrates are mixed at the same times at various percentages. The most common is when a major basic substrate like manure or municipal waste is mixed and digested with a minor substrate which is in smaller percentages (Amon *et al*., 2007).

Co-digestion of MSW with other types of waste is an interesting alternative to improve biogas production to obtain a more stable process and to achieve a better handling of waste. However it comes with some disadvantages like transport costs of co-substrate, additional pre-treatment facilities and the problems arising from the harmonization of the waste generators. The key factor of successful co-digestion is that the balance of macro and micro nutrients can be assured by the co- substrate. The use of co-digestion improves the amount of biogas produced both in quantity and quality. This is as result of the supply of the missing and necessary nutrients (Mata-Alvarez *et al*., 2003).

2.9.1 Advantages of co-digestion

Several ecological, technological and economical advantages may be realized from co-digestion, these include; Improved nutrient balance and digestion, equalization of particulate through dilution by manure or municipal waste, additional biogas collection, possible gate fees for waste treatment, large market for maize cobs and their residues.

Co-digestion can provide a better nutrient balance and therefore better digester performance and higher biogas yields (Luostarinen *et al.*, 2009). The combination of waste and poultry manure had been found to be capable of maintaining a proper Carbon Nitrogen ratio in the reactor (Murto *et al*., 2004), highly buffered system was obtained by co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste and the process worked well with increased gas yields.

Waste with poor fluid dynamics, aggregating wastes, particulate materials, floating wastes or materials with high disturbing or inhibiting components can be utilized more effectively as co substrates when co-digest with well performing municipal or liquid manure (Luostarinen *et al.*, 2009).

The addition of maize cobs or silage as co-substrates allows for further increase in the biogas Productivity of agricultural digesters (Krueger *et al.,* 2011). Animal manure usually contains high ammonia concentration that has an inhibitory effect on the glycolytic pathway. Co-digestion of plant material and manures, manures provide buffering capacity and a wide range of nutrients, while the addition of plant material with high carbon content balances the carbon to nitrogen (C/N) ratio of the feedstock, thereby decreasing the risk of ammonia inhibition (Lebuhn *et al*., 2007).

2.9.2 Limitations of co- digestion

The limitations for anaerobic digestion have been reported to include; increased digester effluent, additional pretreatment requirements, increased mixing requirements, hygienization requirements and waste water treatment requirement. The pH of the digester should be controlled at the methanogenic phase; otherwise production of biogas may not be possible (Mata-Alvarez *et al.*, 2005). Anaerobic digesters fed with cow manure and varying proportions of wheat straw produced the highest specific methane yields has observed with 40% of wheat straw of total solids (TS) in the feedstock.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study Location

The study was carried out in Ruiru town in Ruiru Sub of County Kiambu County which is located at latitude 10 01", longitude 370 05''and an altitude of 1494m above sea level (Robinson *et al.*, 2005). The feedstock was collected in Ruiru but the analysis of feedstock and laboratory tests was carried out at department of chemistry laboratories of Jomo Kenyatta University of Agriculture and Technology and Kenya Industrial Research Institute (KIRDI) laboratories in Nairobi while the digestion was done at Mount Kenya University Chemistry laboratories in Thika. The analysis of gas for determination of the amounts of carbon dioxide and methane was done at Kenya Industrial Research Institute (KIRDI) – Nairobi.

Figure 3.1 Map of Ruiru Town.

3.2 Research Design

In this study, the main research questions were addressed using both experimental analysis for data collection and statistical analytical techniques combined with qualitative and descriptive approaches.

Experimentation enables gathering of data in form of results at a particular point in time with the intention of describing the nature of existing conditions or identifying standards against which existing conditions can be compared or determining the relationship that exist between specific events (Cohen and Marion, 2007). In this study the Experiment method was used to establish the major composition of municipal solid waste and its effect on biogas production and how the output could be improved with addition of maize cobs. The study further sought to check the extent to which the quality of the gas was improved through co-digestion.

3.3 Feedstock Preparation

Dry maize cobs were obtained from a farmland of Kenya Agricultural Research institute (KARI) Ruiru farm. The maize cobs were sun-dried and further dried in an oven at 60 ^{0}C for 2 days to eliminate moisture.

The cobs were then crushed in a mortar with pestle before being taken to the mill for grinding to reduce their particle sizes and hence increase the surface area for further degradation. The MSW was taken from the dump site where it was carefully selected to ensure that only biodegradable components of the waste were selected. MSW mostly comprised of vegetable waste, Kitchen waste, slaughter house waste and other biodegradable waste comprising the Organic Fraction of Municipal Solid Waste (OFMSW). The waste used for laboratory-scale experiments was collected on one occasion. This study did not find any evidence that municipal waste in Ruiru has been sampled in the past. The waste composition is an important factor in determining which types of waste-to-energy conversion methods are possible, thus sampling of municipal solid waste was performed in the designated dumping site in Ruiru. Demographics often have a major impact on the waste stream composition thus, sampling of the waste stream that came from different locations in Ruiru was sampled and. The municipal solid waste characterization was performed by site-specific sampling. Site-specific sampling was performed according to the standard testing methods for Determination of the Composition of Unprocessed Municipal Solid Waste ASTM D5231 – 92 (2008) on five occasions. The waste was sieved through a 1.6 mm sieve to separate the liquid slurry from the solids, the filtrate was weighed i.e. x kg while the liquid slurry was evaporated and the remaining solids weighed i.e. y kg. The sum of x and y (x + y = Total solids) formed the total solids of the substrate and results recorded in Tables 4.1, 4.2 and 4.3. Both fractions were retained as feedstock for the experiments.

3.3.1 Analysis of volatile solids

The physical and chemical compositions of the undigested maize cobs and MSW were determined in laboratory before digestion and results recorded in the Tables 4.2 and 4.3.

To determine the fraction of volatile solids in the substrate which is the maximum that can possibly be degraded, aluminium bowl was used. First an aluminium bowl was weighed and its weight recorded. Secondly the bowl was weighed with an organic sample (bowl + sample substrate) and dried to 105°C in an oven. The components were cooled and measured. The mixture was ashed in a 550°C furnace and cooled. The bowl was weighed together with the ash (bowl + ash).The difference between the weights (bowl +VS + ash) – (bowl + ash) is the fraction of volatile solids in the feedstock sample substrates. This was done for both the MSW and the maize cobs. The average result for inoculums, MSW and maize cobs were arrived at from three rounds of measurements for three different samples of each substrate and recorded in Tables 4.1, 4.2 and 4.3 respectively.

3.3.2 Measurement of Nitrogen

Nitrogen was determined using the Micro-Khjedal Method. The nitrogen levels were used to determine the amount of proteins in the slurries. The M-Khjedal method involved the digestion of the slurry where the sample was reacted with H_2SO_4 in the presence of a catalyst to produce ammonia. It was followed by distillation where the ammonia ions from digest were converted to ammonia gas by addition of NaOH. Finally the acid gas was titrated with NaOH in the presence of a dye and the amount of base used to calculate the ammonia in the original solution.

The number of moles of ammonia in the final solution is equal to those of nitrogen multiplied by 14 (the atomic mass of nitrogen) to determine the grams of nitrogen. The pH of the slurries was measured using Pocket-sized pH meter model 02895 A1 (Hanna Instruments). The pH of the samples was used to indicate the acidity or alkalinity of the samples. The measurement of VS, nitrogen and pH was carried in the chemistry laboratory of Mt. Kenya University – Thika. The other components of the substrates (MSW, inoculums and maize cobs) like iron (Fe), carbon (C), Nickel (Ni) and Phosphorous (P) were done using an elemental Analyzer at Kenya Industrial Research and Development Institute (KIRDI)- Nairobi and average results recorded.

3.4 Inoculums

The inoculums for the laboratory-scale experiment were collected from a full scale digester in Ruiru and had its PH, partial alkalinity and total alkalinity determined. Other characteristics of the inoculums were measured and recorded.

The effluent from the continuous laboratory-scale experiments was used as inoculums in the biochemical methane potential (BMP) tests.

3.5 Experimental setup and operational protocol

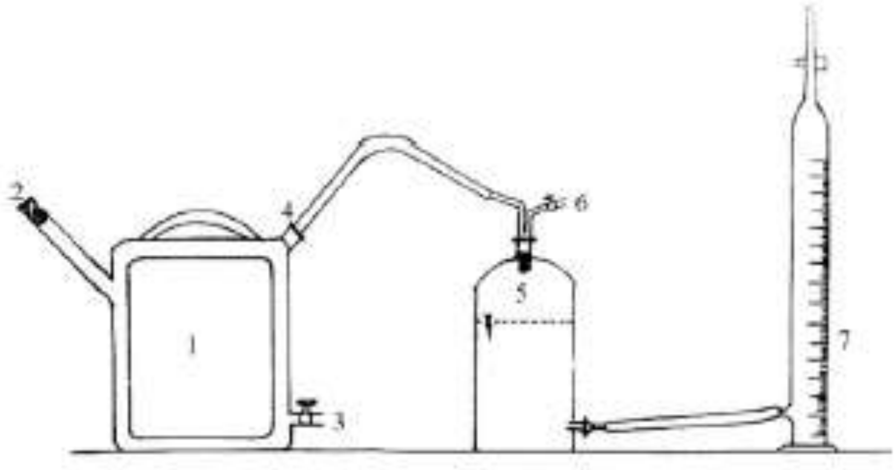

Figure 3.2 Experimental set-up adopted in the study.

1. Digester (*V*=2L) capacity
2. Feed inlet
3. Liquid sampling point
4. Gas opening
5. Water displacement jar
6. Gas outlet
7. Measuring jar

A schematic representation of the experimental set up is as shown in Figure 3.2.The experimental set up comprised five different experiments for the digestion of maize cobs, MSW and co digestion of MSW and maize in the ratio of 1:1, 2:1 and 3:1.The components were mainly a two liter capacity beaker that served as a digester with a feedstock sampling point at the bottom side and a gas outlet at the top side, a feed inlet pipe, gas outlet and a graduated measuring jar. The gas outlet pipe was fitted with a valve to control the gas flow.

3.6 Monitoring of the Laboratory Experiment.

The laboratory digester was a mesophillic plant operating at medium temperatures. The process was fed continuously once a day. The designed maximum daily addition was 0.25 liters with a maximum Total Solids (TS) content determined. The waste was mixed in a separate container in the required ratio before feeding. The material inflow and the raw gas volume were monitored by ensuring a particular and regular feeding and recording the gas output. The methane content of the gas and the TS in the waste was monitored also, once a day for a whole week. The chemical composition of the feedstock was analyzed and the values were used to calculate the operational conditions.

3.7 Biochemical Methane Potential (BMP) Tests

The potential methane production of the feedstock was investigated in a Biochemical Methane Potential trial. The Municipal Solid waste and maize cobs were digested separately and in combination with the MSW (base feedstock) at different ratios. All tests were performed in triplicate at room temperature. The ratio of the inoculums Volatile Solids to substrate Volatile Solids was set at 2:1 in the control, and the corresponding wet weight of each feedstock calculated using the data from the measurements. Mixtures of MSW and maize cobs, at a Volatile Solids ratio of 1:1, 2:1 and 3:1 were investigated in the co-digestion trials to ascertain the best composition.

Before starting/performing the analyses, anaerobic conditions were established by sparging with nitrogen gas prior to corking of the flasks. The experiments were terminated after 10 days of incubation when the methane production rate in all assays had decreased below average as shown in Table 4.4.

3.7.1 Laboratory experiments

The laboratory experimental setup consisted of three set-ups similar to the one in Figure 3.2 The biogas produced was monitored and determined from the amount of water displaced into the graduated jar. The reactors were initially inoculated with seed sludge from the full-scale process. . The filtered fraction of the MSW was fed to the reactors once a day (quarter liter per day in total). The solid fractions (5g) were fed manually with a homemade-100 ml plastic syringe every day through a port on the side of the reactor. The total amount of feedstock added per day (solid and liquid fractions) was 1035g, from which the corresponding Organic Loading Rate (OLR) was determined and Solid Retention Time (SRT) in days calculated. These conditions were maintained in all the three reactors for a period of 10 days.

(a) (b)

Figure 3.3 (a) and (b) Experimental set up for laboratory scale biogas production

3.8 Analytical methods

The non condensable gases were tested according to the American Standard Test method ASTM D2504-88(1998) in KIRDI laboratories using a gas chromatograph thermal conductivity detector (GC-TCD) model Shimadzu GC-8A and gas chromatography flame ionization detector (GC-FID) model Shimadzu GC-9A. An isocratic mode was used since a constant temperature was maintained throughout the operation. The detector initial and final temperature was set as 150^oC. The column was set and maintained constant throughout the operation time, with an initial temperature of 120^oC. Sufficient time of 1 hour was allowed for temperature stabilization before the start of analysis. Samples of the syngas were collected from the pipeline connected to the reactor into evacuated clean containers.1 ml of the sample was injected into a gas chromatograph (GC-TCD) and the CO_2, CO, CH_4, H_2, N_2, and O_2 concentrations were determined using a (TCD). Calibration gases were prepared in helium by marking the appropriate dilutions and a standard curve for the concentration versus peak area values was obtained for each standard gas. Sample concentrations were obtained from the appropriate calibration curves. For compound identification, standard gases for each gas sample were used.

a

b

Figure 3.4 (a) and (b) Laboratory measurement of feedstock nutrients and elemental composition using a gas chromatography detector (GCD) and a bomb calorimeter.

TS, VS, and pH were determined according to standard methods for the examination of water and waste water (APHA, 1995). Biogas composition was determined by gas chromatography. The biogas composition test was done for both the MSW, maize cobs and for the three ratios of mixing. The total gas volume was measured using a graduated 100-ml gas-tight glass syringe with a sample lock in the batch experiments. Methane and biogas yield were calculated as the net amount of methane produced per unit of volatile solids added to the digester.

The MSW was analyzed at the Jomo Kenyatta University of Agriculture and Technology (JKUAT) chemistry laboratories, to determine crude fat and protein content. All VS that are not fat or proteins were assumed to be carbohydrates. The concentrations of macro and micro nutrients were analyzed in the industrial waste and the fresh crops using elementary analysis for Nitrogen (N) content and the C: N ratio determined.

3.9 Statistical analysis

The data was by measurement and experimentation whose results were coded and tabulated for analysis. Analysis involved use of descriptive statistics, covariate correlation and cross tabulation. The data was summarized into frequencies and percentages and presented in Tables, bar charts and Figures. Standard deviations were used to show closeness and usefulness of the data from experiments. Frequencies and percentages were adopted to present, discuss and interpret findings obtained.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter the findings of the study/experiments are tabulated and discussed as per objectives.

4.1 Feedstock properties

The results of the feedstock nutrient composition determination are tabulated in Tables 4.1, 4.2 and 4.3.

Table 4.1: Characteristics of materials used as inoculum for experiments.

	Inoculum			
	1	2	3	Average
TS (%kg of substrate)	31.3	31	30	30.7± 0.68
VS (% of TS)	18	19	21	19.3± 1.53
PH (% of TS)	9.1	8.8	8.9	8.9± 0.15
Nitrogen (% of TS)	2.2	1.8	2.0	1.9 ± 0.12
Carbohydrates (% of TS)	41	38	39	39± 1.53
Carbon (%of TS)	11	11.3	10.5	11± 0.41
Fe (% of TS)	0.03	0.032	.03	.03± 0.01
Ni (% of TS)	0.002	0.002	.002	.002± 0.00
P (% of TS)	1.5	1.5	1.55	1.5± 0.03

Table 4.2: Characteristics of MSW used as feed stock for experiments.

	Municipal Solid Waste (MSW)			
	1	2	3	Average
C:N Ratio	13	13	13.5	13± 0.29
TS (% of 1 kg of Substrate)	92	91	88	90.3± 2.08
VS (% of TS)	80	80	82	80.7± 1.16
PH (% of TS)	8.1	8.0	8.1	8.0± 0.06
Nitrogen (% of TS)	1.5	1.55	1.48	1.51± 0.04
Carbohydrates (% of TS)	56	57.0	53	55.3± 2.08
Carbon (%of TS)	19.6	20.2	20	19.9± 0.31
Fe (% of TS)	.03	.033	.033	.03± 0.00
Ni (% of TS)	.0021	.002	.002	.01± 0.00
P (% of TS)	1.6	1.4	1.3	1.4± 0.15

Table 4.3 : Characteristics of Maize cobsused as feed stock for experiments.

	Maize Cobs			
	1	2	3	Average
C:N Ratio	37	38	37	37. 5 ± 0.58
TS (% of 1 kg of substrate)	94	96	92	94± 2.00
VS (% of TS)	91	92	92.2	91.7± 0.64
PH (% of TS)	5.0	5.0	5.0	5.0± 0.00
Nitrogen (% of TS)	0.7	0.68	0.69	0.7 ± 0.01
Carbohydrates (% of TS)	71.2	71.3	71	71.2± 0.15
Carbon (%of TS)	26.1	26	26	26.0± 0.06
Fe (% of TS)	-	-	-	-
Ni (% of TS)		-	-	-
P (% of TS)		-	-	-

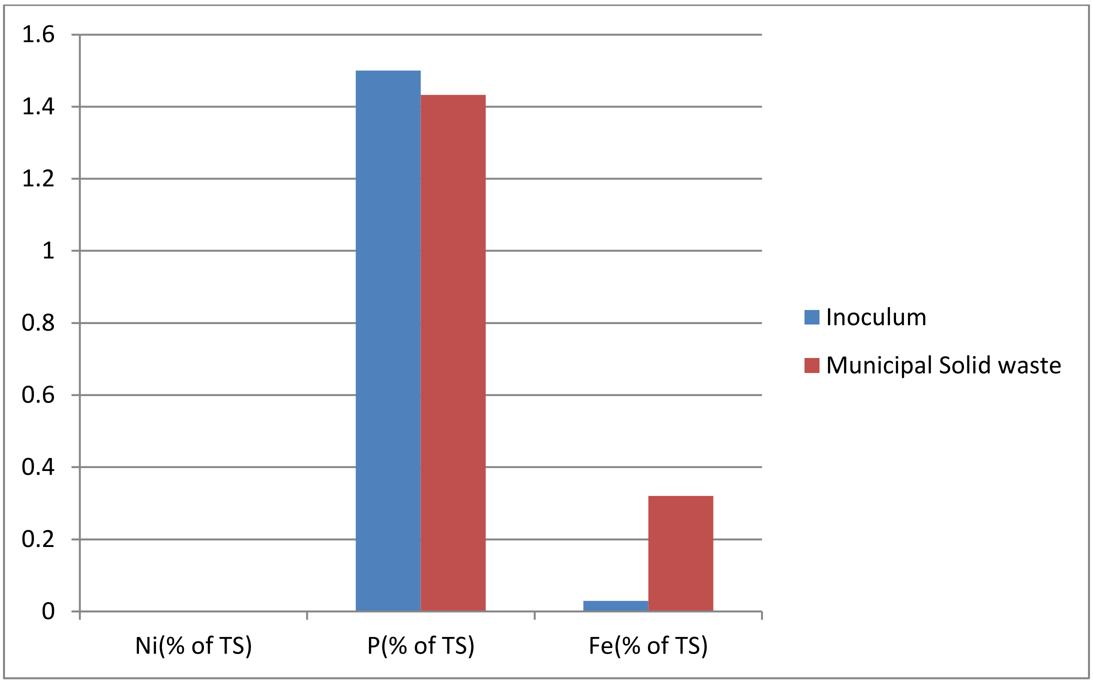

Figure 4.1 Elemental composition of MSW, Maize Cobs and inoculum

The composition and the nutrient content in the feedstock used in the study are given in Tables 4.1, 4.2, 4.3. MSW had a high fat content and a C: N ratio of 13 while maize cobs had a high content of carbohydrates and a C: N ratio of 37. The optimum C: N ratio for anaerobic digestion has been reported to be between 16 and 20 (Alvarez *et al*., 2010; Mshandete *et al*., 2004). This means that neither MSW nor Maize Cobs supports a suitable C: N for proper anaerobic digestion. MSW also had a higher amount of all the macro- and micronutrients investigated, and a very high content of N, P, Ni and Fe as compared to the maize cobs. The maize cobs, on the other hand, were poor in essential micronutrients, with C: N ratio of 37.The MSW and maize cobs recorded a pH of 8.0 and 5.0 respectively.

MSW and maize cob are both rich in volatile solids at 90.3% of TS and 94% of TS respectively.

This means that both MSW and maize cobs are suitable feedstock for Anaerobic Digestion with potential for sustainable biogas production. It’s also clear that due to lack of the necessary micro and macro nutrients for anaerobic digestion Maize cobs may not be suitable to digest alone. On the other hand the poor C: N ratio of MSW makes it unsuitable for digestion alone due to process imbalance.

4.2 Biogas Yield

The MSW and maize cobs were digested separately and co digested in the ratio of 1:1, 2:1 and 3:1 as shown in Figure 3.3 and the results recorded in Table 4.4.The maize cobs had a cumulative yield of 6.1 cm^3 for the 10 days of digestion while MSW had a cumulative yield of 34 cm^3 for the same number of days under the same conditions. The low yield from maize cobs were attributed to lack sufficient micro and macro nutrients in the cobs and the lignin which prevents further degradation of the cobs (Pakarinen *et al.*, 2008)

When the maize cobs were co digested with municipal solid waste with MSW as the base feed stock the results were improved. MSW: Maize Cobs in ratios of 3:1, 2:1, and 1:1 yielded 58 cm^3, 101 cm^3 and 39 cm^3 respectively. The 58cm^3 yield for ratio 3:1 which was more improved that that of ratio 1:1 and those of maize cobs and municipal solid waste digested separately indicate that there a better balance of digestion conditions. It was shown that when these feed stocks are digested in the ratio of 1:1 the effect of maize is still significant. The digestion in the ratio of 2:1 showed a significant improvement compared to all other combinations hence a better balance of anaerobic conditions. The Macro and micronutrients present in the MSW were sufficient to penetrate the lignin hence high yields.

Table 4.4: Biogas Yields in cm^3 for various types of feedstock.

	Maize cobs		MSW		MSW and Maize Cobs in the ratio of 3:1		MSW and Maize Cobs in the ratio of 2:1		MSW and Maize Cobs in the ratio of 1:1	
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	3	3	6.5	6.5	15	15	23	23	13	13
2	1.5	4.5	4.0	10.5	8	23	15	38	6	19
3	1	5.5	4.0	14.5	7	30	12	50	4	23
4	0.5	6.0	3.0	17.5	5	35	9	59	4	27
5	0.1	6.1	3	20.5	5	40	7	66	3	30
6	0	6.1	3	23.5	4	44	7	73	3	33
7	0	6.1	2	25.5	3	47	7	80	3	36

	Maize cobs		MSW		MSW and Maize Cobs in the ratio of 3:1		MSW and Maize Cobs in the ratio of 2:1		MSW and Maize Cobs in the ratio of 1:1	
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
8	0	6.1	2.5	28	3	50	7	87	1	37
9	0	6.1	3	31	4	54	7	94	1	38
10	0	6.1	3	34	4	58	7	101	1	39

4.3 Biogas Analysis

The analysis of the biogas was done using a Gas Chromatography with a thermal conductivity detector for each product of the experiment to determine the composition of the gas.

Table 4.5: Biogas from Maize Cobs.

PARAMETER	MAIZE COBS			
	1	2	3	Average
Hydrogen (H_2)	2.7	2.6	2.8	2.7 ± 0.10
Hydrogen Sulphide (H_2S)	3.2	2.8	3.6	3.2 ± 0.40
Carbon dioxide (CO_2)	32	34.8	36	34.3 ± 2.05
Methane (CH_4)	48	47.5	49	48. 2 ± 0.76
Nitrogen (N_2)	2.35	2.5	2.3	2.4 ± 0.10

Table 4.5 shows results of the composition of the digested gas from maize cobs. The results indicate that the process yielded a gas composition at average 48. 2 ± 0.76% methane (CH_4), 34.3 ± 2.05 carbon dioxide (CO_2) while the other gases present in the biogas including hydrogen, Nitrogen and hydrogen sulphide occupied 17.5 %. This shows the quality of the gas is compromised by the larger fraction of other gases and the higher amounts of CO_2 in the final product.

Table 4.6: Biogas from MSW

PARAMETER	MUNICIPAL SOLID WASTE (%)			
	1	**2**	**3**	**Average**
Hydrogen (H_2)	2.3	2.32	2.3	2.3± 0.01
Hydrogen Sulphide (H_2S)	3.4	3.45	3.35	3.4± 0.05
Carbon dioxide (CO_2)	24.2	24.8	25.6	24.8± 0.70
Methane (CH_4)	50.7	50.4	51	50.7± 0.30
Nitrogen (N_2)	5.3	4.9	5.1	5.1± 0.20

Table 4.6 shows results of the composition of the digested gas from Municipal Solid Waste. The results indicate that the process yielded a gas composition of 50.7± 0.30% methane (CH_4), 24.8± 0.70% carbon dioxide (CO_2) and the other gases present in the biogas including hydrogen, Nitrogen and hydrogen sulphide occupied 22.45 %. The gas showed very high amounts of other gases with a relatively improved percentage of methane and a largely reduced percentage of carbon dioxide. The reduced carbon dioxide was attributed to the poor amounts of carbon in the composition of MSW as shown if Figure 4.2.

Table 4.7: Biogas from MSW and Maize Cobs in the Ratio of 3:1

PARAMETER	MSW AND MAIZE COBS IN THE RATIO OF 3:1			
	1	**2**	**3**	**Average**
Hydrogen (H_2)	2.5	2.0	2.4	2.3 ± 0.27
Hydrogen Sulphide (H_2S)	3.4	2.8	3.4	3.2 ± 0.35
Carbon dioxide (CO_2)	25.6	26.3	26.1	26 ± 0.36
Methane (CH_4)	52	52.4	51.6	52 ± 0.40
Nitrogen (N_2)	4.6	5.0	4.8	4.8± 0.20

Table 4.7 shows results of the composition of the digested gas from Municipal Solid Waste and maize cobs in the ratio of 3:1 respectively. The results indicate that the process yielded a gas composition of 52 ± 0.40% methane (CH_4), 26 ± 0.36% carbon dioxide (CO_2) and the other gases present in the biogas including hydrogen, Nitrogen and hydrogen sulphide occupied 22 %. The percentage of methane and CO_2 increased by almost 2% each compared with the gas from MSW which occupied 2/3 of the feedstock composition. The slight increase in carbon dioxide is as a result of the carbon injected by the addition of maize cobs.

Table 4.8: Biogas from MSW and Maize Cobs in the Ratio of 1:1

PARAMETER	**MSW AND MAIZE COBS IN THE RATIO OF 1:1**			
	1	**2**	**3**	**Average**
Hydrogen (H_2)	2.4	2.2	2.6	2.4 ± 0.20
Hydrogen Sulphide (H_2S)	3.0	3.0	3.0	3.0 ± 0.00
Carbon dioxide (CO_2)	27.2	27.1	27.2	27.2 ± 0.58
Methane (CH_4)	54	54.1	54	54 ± 0.58
Nitrogen (N_2)	4.2	4.1	4.3	4.2 ± 0.10

Table 4.8 shows results of the composition of the digested gas from Municipal Solid Waste and maize cobs in the ratio of 1:1. The results indicate that the process yielded a gas composition of 54 ± 0.58% methane (CH_4), 27.2 ± 0.58% carbon dioxide (CO_2) and the other gases present in the biogas including hydrogen, Nitrogen and hydrogen sulphide occupied 18.8 %. The percentage of methane and CO_2 increased by almost 2% and 1% respectively compared to the results of Table 4.7.The percentage of other gases in this product dropped significantly indicating a more balanced feedstock into the digester. The percentage of methane in this product is still short of one 1% to reach the minimum of the recommended quality of gas while carbon dioxide remained within range (Cavinato *et al*., 2010*).*

Table 4.9 : Biogas from MSW and Maize Cobs in the Ratio of 2:1

PARAMETER	**MSW AND MAIZE COBS IN THE RATIO OF 2:1**			
	1	**2**	**3**	**Average**
Hydrogen (H_2)	2.3	2.3	2.3	2.3 ± 0.00
Hydrogen Sulphide (H_2S)	2.8	2.6	3.0	2.8 ± 0.20
Carbon dioxide (CO_2)	33	29	28	30 ± 2.65
Methane (CH_4)	58	58	59	58.33 ± 0.58
Nitrogen (N_2)	3.0	3.0	3.0	3.0 ± 0.00

Table 4.9 shows results of the composition of the digested gas from Municipal Solid Waste and maize cobs in the ratio of 2:1. The results indicate that the process yielded a gas composition of 58.33 ± 0.58% methane (CH_4), 30 ± 2.65% carbon dioxide (CO_2) and the other gases present in the biogas including hydrogen, Nitrogen and hydrogen sulphide occupied 11.67 %. The percentage of methane and CO_2 increased by almost 4% and 3% respectively compared to the results of Table 4.8.The percentage of other gases in this product dropped by almost 7% indicating a well balanced feedstock into the digester. The gas was analysed by gas chromatography coupled with a thermal conductivity detector.

In general results obtained for the biogas production from MSW, Maize cobs and the mixture in various ratios indicated that neither maize nor MSW produce quality biogas on their own. Quality biogas should comprise methane (CH_4) in the range of 55% -65% while carbon dioxide (CO_2) should be in the range of 25% - 35%. It can be seen from Table4.0.5 that biogas constituents from maize cobs comprise of 48% CH_4 and 34.8% CO_2 while 17.2% are other impurities. These percentages are below and above the theoretical values of quality biogas. On the other hand the digestion of MSW alone yielded biogas composed of 50.7% CH_4 and 24.8% CO_2 which also does not measure up to the minimum theoretical standards. For co- digestion of MSW and maize cobs in the ratios of 3:1, 1:1 and 2:1 as recorded in Tables 4.0.7/8/9 it shows that ratio 2:1 presents a composition which is better compared with all the others ratios and the those from the independent digestion of maize cobs and MSW. This combination of feedstock produced biogas composed of 58.33 ± 0.58% CH_4 and 30 ± 2.65 CO_2 which is well within the acceptable ranges (Cavinato *et al* 2010). It can be seen that the composition of feedstock has a significant effect on the quality of the product (biogas).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The general objective of this study was to investigate the potential benefits of MSW and maize cobs co-digestion. The study found out that MSW for Anaerobic Digestion varies considerably in composition both qualitatively and quantitatively. To achieve better results it is important to consider balancing the total solids, volatile solids and the C: N ratio when selecting feedstock for Anaerobic Digestion. Products like Volatile Fatty Acids, Hydrogen Sulphide (H_2S), ammonia and other inhibitory components must be carefully controlled in order to achieve excellent results. For this study it was noted that both maize cobs and MSW have reasonable amounts of Total Solids and Volatile Solids with a large variation in C: N ratio of 37 for maize cobs and 13 for MSW while the ideal range should be between 16 and 20.

Maize cobs require effective pretreatment of cutting and grinding while MSW require sorting prior to digestion. In determining the BMP it was noted that maize cobs digested alone yielded high amounts of biogas in the first three days which dropped significantly in the subsequent days due to lignin which inhibits reaction while MSW was affected by the poor C: N ratio. Co- digestion of MSW and maize cobs at the ratio 2:1 showed significant improvement in biogas yield with moderated values of C: N ratio making the process reliable and economical.

Analysis of the composition and to a greater extent the quality of the biogas from the maize cobs, MSW and co- digestion showed little variation although the amounts of other components like hydrogen, H_2S and carbon monoxide appeared to vary considerably. There was a good balance between carbon dioxide and methane of biogas in co-digestion especially for the 2:1 of MSW and maize cobs digestion.

5.2 Recommendations

The MSW generated should be separated at the source to make it easy to sort the waste during application of a given waste to an appropriate energy recovery technology. The concept of co-digestion can result into adequate, reliable and quality biogas. It is also recommended that co-digestion can be used as a means of turning Municipal solid waste into a more useful resource since waste which otherwise would have required resources to dispose will be a source of renewable energy and may create employment for the population that will work in the plant.

The study was carried out in laboratory and in small scale where most of the digestion conditions were controlled; it is therefore recommended that a full and large scale digestion be carried under uncontrolled conditions to validate the study findings to make them widely acceptable.

The three experiments of co-digestion of ratio 3:1, 1:1, 2:1 did not interpolate Figures between 1, 2 and 3 i.e. 2.5:1.5 among others, it is recommended that more experiments be carried out to determine the characteristics of other ratio mixtures to check whether there is any other ratio with better results to validate the study.

It is also recommended that further studies be carried out to determine which other energy crops and their residues can be used to supplement MSW anaerobic digesters to enhance biogas production.

.

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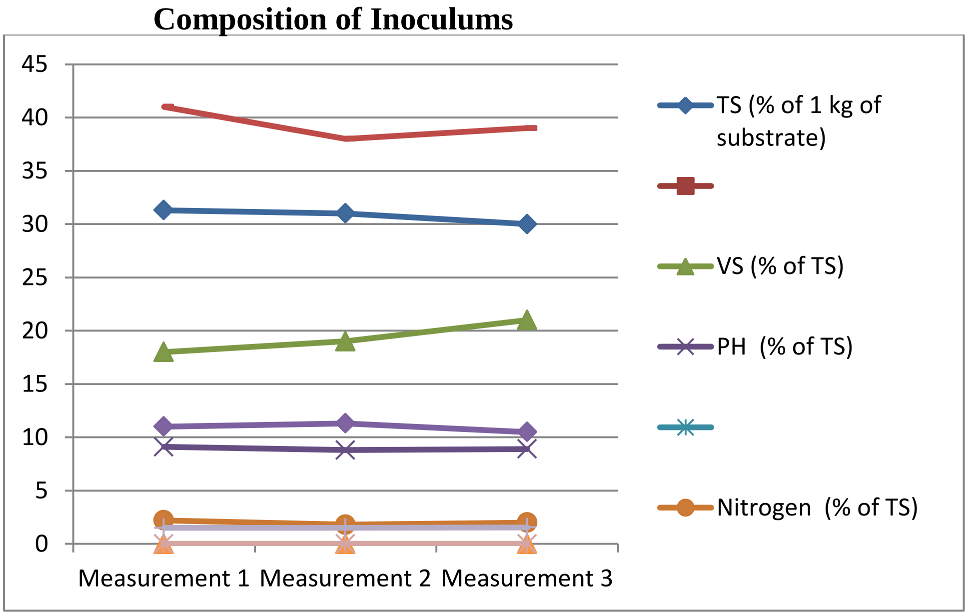
APPENDICES

Appendix A: Composition and characteristics of inoculums.

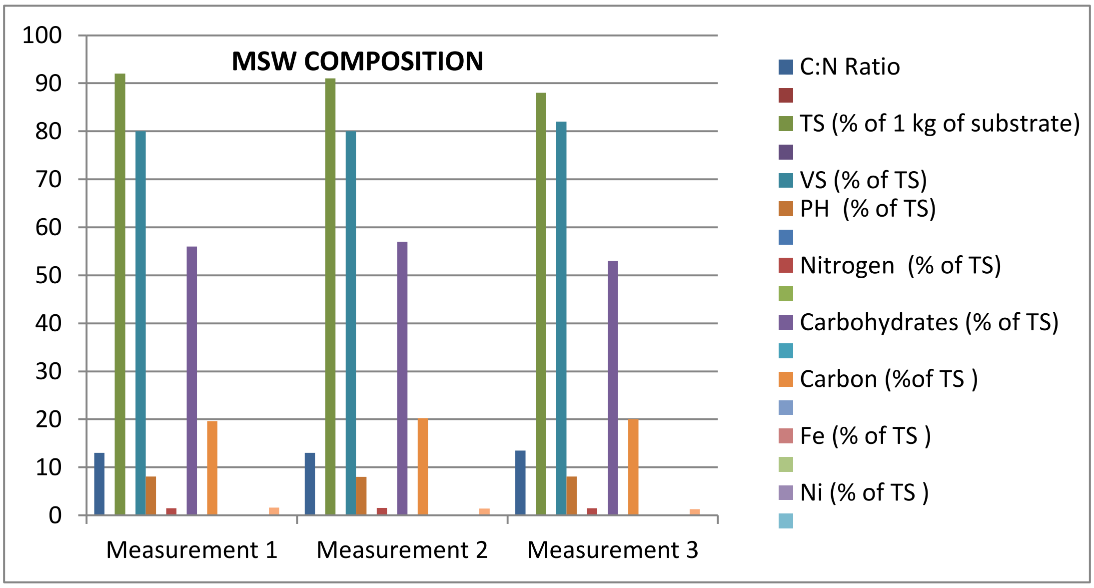
	Measurement 1	Measurement 2	Measurement 3
TS (% of 1 kg of substrate)	31.3	31	30
VS (% of TS)	18	19	21
PH (% of TS)	9.1	8.8	8.9
Nitrogen (% of TS)	2.2	1.8	2.0
Carbohydrates (% of TS)	41	38	39
Carbon (%of TS)	11	11.3	10.5
Fe (% of TS)	.o25	.o32	.o29
Ni (% of TS)	.002	.0023	.00203
P (% of TS)	1.5	1.5	1.55



Composition of Inoculums

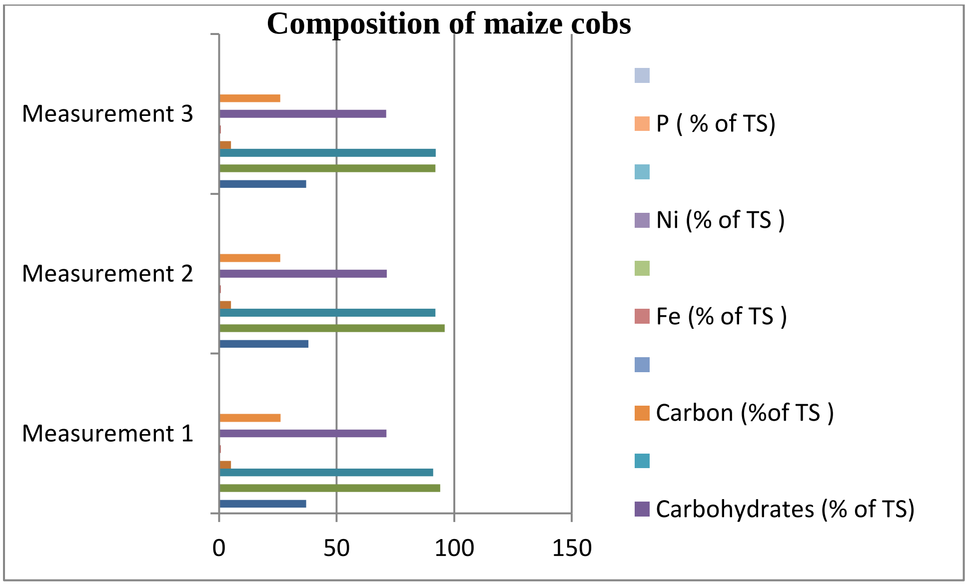
Appendix B: Composition and characteristics of Municipal Solid Waste

	Measurement 1	Measurement 2	Measurement 3
C:N Ratio	13	13	13.5
TS (% of 1 kg of substrate)	92	91	88
VS (% of TS)	80	80	82
PH (% of TS)	8.1	8.0	8.1
Nitrogen (% of TS)	1.5	1.55	1.48
Carbohydrates (% of TS)	56	57	53
Carbon (%of TS)	19.6	20.2	20
Fe (% of TS)	.03	.033	.033
Ni (% of TS)	.0021	.0016	.002
P (% of TS)	1.6	1.4	1.3



Appendix C: Composition and characteristics of Maize Cobs

	Measurement 1	Measurement 2	Measurement 3
C:N Ratio	37	38	37
TS (% of 1 kg of substrate)	94	96	92
VS (% of TS)	91	92	92.2
PH (% of TS)	5.0	5.0	5.0
Nitrogen (% of TS)	0.7	0.68	0.69
Carbohydrates (% of TS)	71.2	71.3	71
Carbon (%of TS)	26.1	26	26
Fe (% of TS)	-	-	-
Ni (% of TS)	-	-	-
P (% of TS)	-	-	-



Appendix D: Laboratory Biogas yield results from digestion of maize cobs

	Maize cobs					
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	3	3	2.8	2.8	2.9	3.2
2	1.5	4.5	1.5	4.3	1.5	4.4
3	1	5.5	0.8	5.3	1	5.4
4	0.7	6.2	0.6	5.9	0.5	5.9
5	0.1	6.3	0.1	6.0	0	5.9
6	0.1	6.4	0	6.0	0	5.9
7	0	6.4	0	6.0	0	5.9
8	0	6.4	0	6.0	0	5.9
9	0	6.4	0	6.0	0	5.9
10	0	6.4	0	6.0	0	5.9

Appendix E: Biogas yield results from digestion of MSW

	Municipal Solid Waste					
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	6.5	6.5	6.5	6.5	7	7
2	4.0	10.5	4.0	11.5	4.0	11
3	4.0	15.5	4.0	16.5	4.0	15
4	3.0	17.5	3.0	18.5	3.0	18
5	3	29.5	3	19.5	4	22
6	3	22.5	3	20.5	4	25
7	2	25.5	2	23.5	2	28
8	2.5	28.5	2.5	27	2.5	30.5
9	3	30	3	31	4	34.5
10	3	32	3	33	3	36

Appendix F: Biogas yield from digestion of MSW and Maize Cobs at the ratio of 3: 1

	MSW and Maize cobs					
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	15	15	14.5	14.5	15	15
2	12	27	8	22.5	11	26
3	7	33	8	30.5	7	30
4	5	38	6	36.5	5	35
5	4	42	5	41.5	5	40
6	4	46	4	45.5	4	44
7	3	49	3	48.5	3	47
8	4	53	3	51.5	3	50
9	4	56	4	54	4	54
10	4	59	4	55.5	4	61

Appendix G: Biogas yield from digestion of MSW and Maize Cobs at the ratio of 1: 1

	Maize cobs					
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	13	13	12	12	14	14
2	6	19	6	19	6	19
3	4	23	4	23	4	23
4	4	27	4	27	4	27
5	3	30	3	30	3	30
6	3	33	3	33	3	33
7	3	36	3	36	3	36
8	1	37	1	37	1	37
9	1	38	1	38	1	38
10	1	39	1	38	1	40

Appendix H: Biogas yield from digestion of MSW and Maize Cobs at the ratio of 2:1

	MSW and Maize Cobs					
Days	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield	Daily Biogas Yield	Cumulative Biogas Yield
1	24	24	16	16	18	20
2	16	36	16	32	14	34
3	15	51	12	44	12	46
4	12	63	11	55	10	56
5	11	74	10	65	10	66
6	9	83	9	74	7	73
7	7	90	7	81	7	80
8	6	96	6	87	6	86
9	6	102	7	94	6	92
10	6	106	6	100	6	98

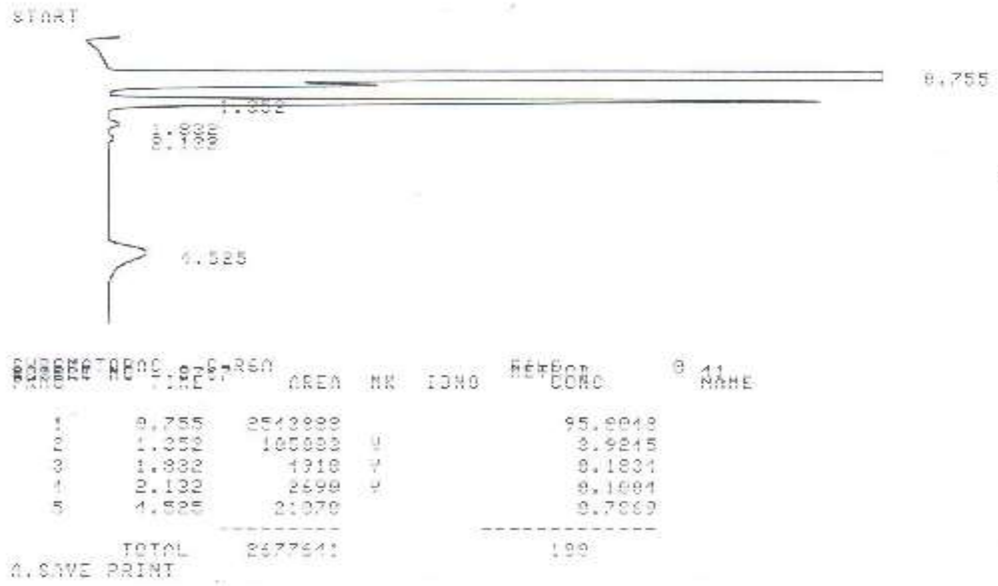
APPENDIX I: Biogas Composition

PARAMETER	**MAIZE COBS**			**MSW**			**MSW: MAIZE COBS (3:1)**		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Hydrogen (H_2)	2.7	2.6	2.8	2.3	2.32	2.3	2.5	2.0	2.4
Hydrogen Sulphide (H_2S)	3.2	2.8	3.6	3.4	3.45	3.35	3.4	2.8	3.4
Carbon dioxide (CO_2)	32	34.8	36	24.2	24.8	25.6	25.6	26.3	26.1
Methane (CH_4)	48	47.5	49	50.7	50.4	51	52	52.4	51.6
Nitrogen (N_2)	2.35	2.5	2.3	5.3	4.9	5.1	4.6	5.0	4.8

PARAMETER	**MSW: MAIZE COBS (1:1)**			**MSW: MAIZE COBS (2:1)**		
	1	**2**	**3**	**1**	**2**	**3**
Hydrogen (H_2)	2.4	2.2	2.6			
Hydrogen Sulphide (H_2S)	3.0	3.0	3.0	2.3	2.3	2.3
Carbon dioxide (CO_2)	27.2	27.1	27.2	2.8	2.6	3.0
Methane (CH_4)	54	54.1	54	33	29	28
Nitrogen (N_2)	4.2	4.1	4.3	58	58	59
Hydrogen (H_2)	**1**	**2**	**3**	3.0	3.0	3.0

APPENDIX J: Thermal gas chromatograms for biogas derived from co-digested MSW and maize cobs at the of 2:1

Appendix 13



```
CHROMATOPAC C-R6A                REPORT      0 41
PKNO  TIME    AREA   MK  IDNO    CONC        NAME

 1    0.755  2543888              95.0048
 2    1.352   105833 V             3.9215
 3    1.832     4318 V             0.1831
 4    2.132     2698 V             0.1004
 5    4.525    21070               0.7869
             ---------        -------------
     TOTAL   2677641             100
A.SAVE PRINT
```

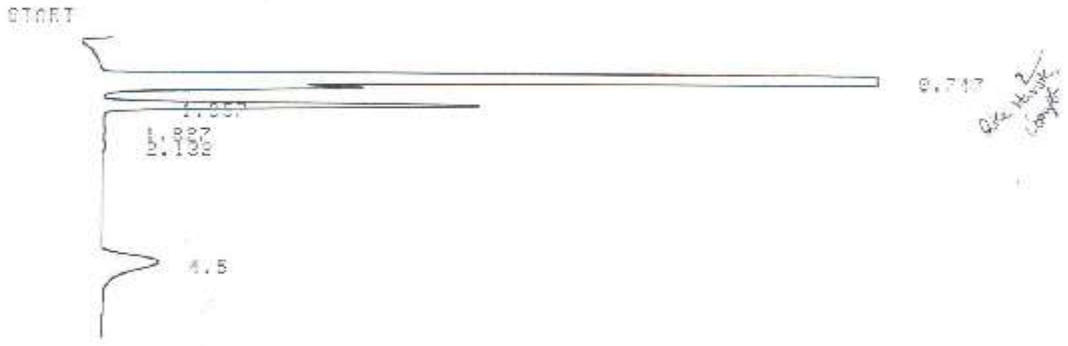
a) Thermal conductivity detector (TCD) plot for saw dust

```
C-R8A CHROMATOPAC   CH=1   DATA=1:@CHRM1.C00        ATTEN= 0   SPEED= 5.0

C-R8A CHROMATOPAC CH=1  Report No.=18    DATA=1:@CHRM1.C00   15/02/23  11:18:41

** CALCULATION REPORT **
CH PKNO    TIME       AREA     HEIGHT   MK  IDNO    CONC            NAME
 1   1     0.842      67802    15770                 99.5161
     2     1.165        115       21    V             0.1682
     3     1.396        215       34    V             0.3157
                  ----------------------         -------------
         TOTAL        68132    15824                100
```

b) Flame ionization detector (FID) plot for saw dust

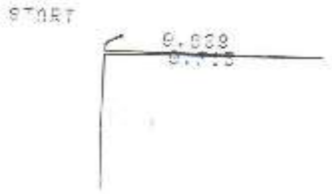
APPENDIX K: The mal gas chromatograms for biogas derived from MSW alone

Appendix 14



```
CHROMATOPAC   C-R6A                     FILE        0
SAMPLE NO   0                           METHOD        41
REPORT NO   8249
PKNO       TIME       AREA   MK   IDNO      CONC         NAME
   1       0.747    3059136                 97.1310
   2       1.057      57629  V               1.8298
   3       1.827       2729  V               0.0864
   4       2.132       2039  V               0.0647
   5       4.5        27945                  0.8873
                  ----------           -------------
          TOTAL     3149468                  100
```

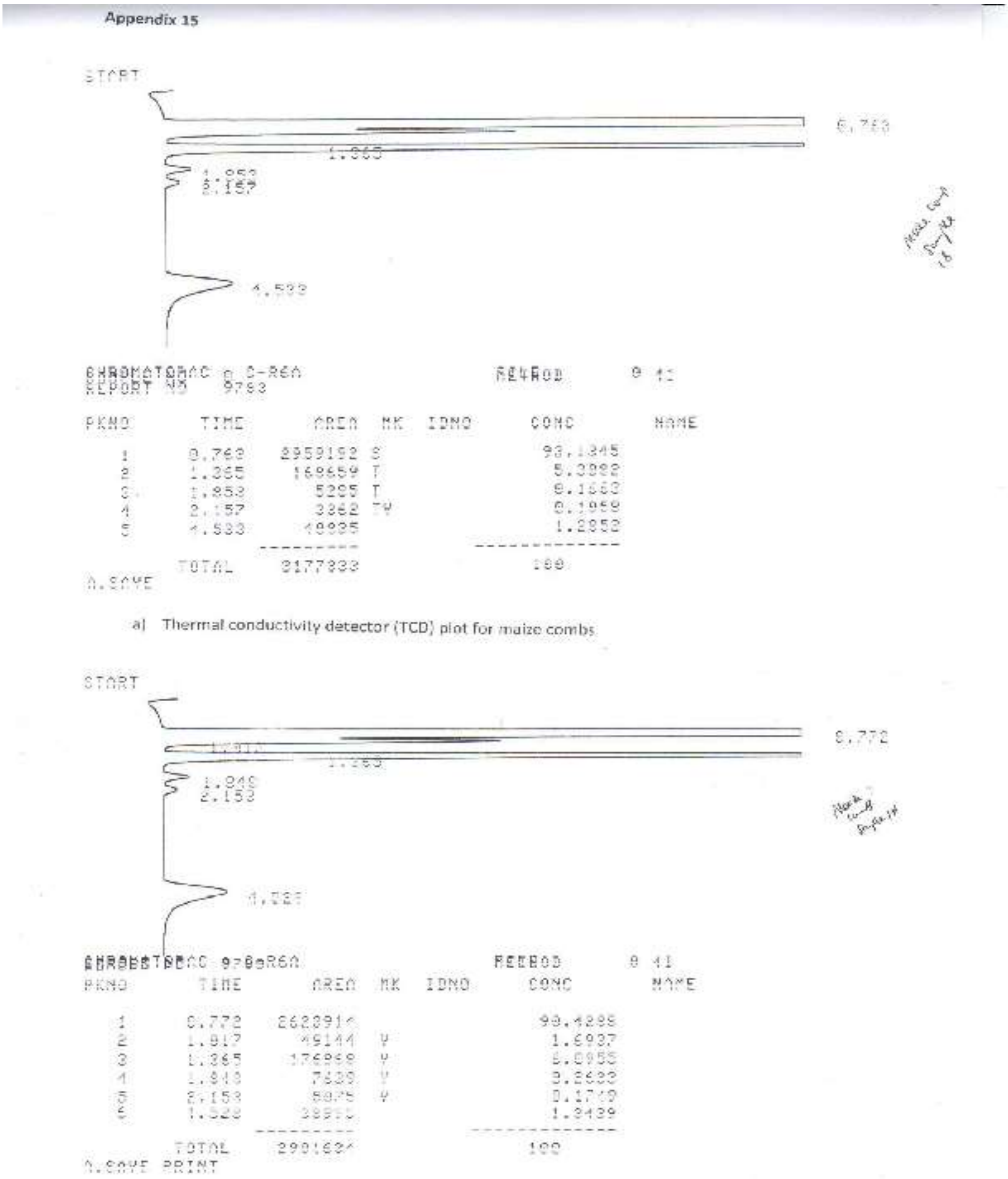
a) Thermal conductivity detector (TCD) plot for rice husks



```
CHROMATOGRAM   1  MEMORIZED

CHROMATOPAC   C-R6A                     FILE        0
SAMPLE NO   0                           METHOD        41
REPORT NO   9955

PKNO       TIME       AREA   MK   IDNO      CONC         NAME

   1       0.039        299                  6.7335
   2       0.715       4142                 93.2665
                  ----------           -------------
          TOTAL        4441                  100
A.SAVE
```

b) Flame ionization detector (FID) plot for rice husks

Appendix L: Thermal gas chromatograms for biogas derived from maize combs alone



Appendix 15

```
CHROMATOPAC C-R6A                          METHOD      0 41
REPORT NO   9793

PKNO      TIME       AREA  MK  IDNO      CONC         NAME

  1      0.763   2959192 S              93.1345
  2      1.365    169659 T               5.3397
  3      1.853      5295 T               0.1666
  4      2.157      3362 TV              0.1058
  5      4.533     39825                 1.2534
                ----------           -------------
         TOTAL   3177333                100
A.SAVE
```

a) Thermal conductivity detector (TCD) plot for maize combs

```
CHROMATOPAC C-R6A                          METHOD      0 41
PKNO      TIME       AREA  MK  IDNO      CONC         NAME

  1      0.772   2623902                90.4295
  2      1.017     49144   V             1.6937
  3      1.365    176869   V             6.0955
  4      1.849      7639   V             0.2633
  5      2.153      5075   V             0.1749
  6      4.528     38995                 1.3439
                ----------           -------------
         TOTAL   2901624                100
A.SAVE PRINT
```