biogas production from black water, kitchen refuse and farm waste

lab assessment and practical application at mcf yatta, kenya

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Master Thesis 30 credits august 2013

NORWEGIAN UNIVERSITY OF LIFE SCIENCES

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15 August 2013, Ås

Preface

The present master thesis is the final product of my two year master program in Environment and Natural Resources - Specialisation Sustainable Water and Sanitation, Health and Development at the Department of Plant and Environmental Sciences (IPM) of the Norwegian University of Life Sciences (UMB). My main supervisor, IPM Professor Petter D. Jenssen, proposed me to work on a project regarding biogas production potential in a farm in Kenya and use the findings as the basis of my thesis. I eagerly accepted, not only because it was on the subject of anaerobic digestion that centers my interest, but also for the prospect of experiencing first-hand how it is like to work in a developing country, where I could put into practice what I have been learning in theory during my studies at UMB.

Mulli's Children Family (MCF) farm at Yatta, Kenya was an appropriate place to serve as case study. There are a number of financial activities going that are usual of small or medium scale farms in Africa. Activities like agriculture, animal husbandry, poultry and fish farming that typically produce waste and wastewater that can serve as substrates for biogas production. Additionally, they face problems that are apparent in the developing world, such as need for clean energy for cooking, lighting and on-site wastewater management.

The experimental procedure for the estimation of biogas potential was designed with the help and guidance of my co-supervisor, Senior Researcher Jon Fredrik Hanssen from the Department of Chemistry, Biotechnology and Food Science (IKBM) of UMB. The choice of substrates was made depending on what was both available at UMB and relevant for the case of MCF. Due to an unforeseen incident at the Vollebekk biogas lab, the experiment took place at the IKBM biogas lab using 0.5 liter bottles, instead of 10 liter lab scale reactors. Time was a limiting factor. An incubation period of 30 days was used that was enough for initiating methane production, but not enough to estimate the ultimate potential. Overall, the conducted lab experiment had a great learning and training value and offered me a deeper understanding in how the process of anaerobic digestion and biogas production works.

Acknowledgments

I would like to thank a number of people that helped me with my master thesis…

… my main supervisor Professor Petter D. Jenssen for his valuable help and guidance.

….my co-supervisor Senior Researcher Jon Fredrik Hanssen for helping me design the lab experiment and offering me his insight and experience on the subject of anaerobic digestion and biogas production. Also, the IKBM department of UMB for opening their doors to me and offering me space and equipment to conduct the lab experiment.

…Dr. Charles Mulli and all the nice people at the MCF farms at Ndalani and Yatta and the offices at Nairobi for their hospitality. It was a great experience.

…Erik E. Hohle and the Energy Farm for making me a part of the MCF project.

…Ragnhild Tjore and Andreas Tutturen for their partnership during the trip in Kenya.

…the lab assistants at the IPM department for their support.

…the IMT department of UMB for providing me the samples for my lab experiment.

…Kirsten Engebakk and Paul Mbole of the Kenyan branch of the Norwegian Church Aid for putting the MCF project in the right perspective.

… Dr. Ann Kingiri, Joan Kariuki and Serah Nderitu of the African Center for Technology Studies (ACTS), for enlightening us regarding the renewable energy policy in Kenya.

…and foremost my parents, Nikos and Eleni, for being supportive and patient all these years of my studies, especially during difficult times.

Abstract

The possibilities for biogas production from black water, kitchen waste and farm waste are examined in this thesis. Theory on the subject of anaerobic digestion and biogas production is presented. Mulli's Children Family (MCF) farm at Yatta, Kenya is used as a real life example. In addition to this, a biogas lab experiment is included.

The available resources for biogas production at MCF Yatta include animal waste, vegetable waste and human waste. The estimated biogas potential of the available resources is 7877 m^3/year or 21.58 m^3/day, assuming 60% methane content. The maximum energy equivalent of the estimated biogas potential is 184.3 GJ. A system for biogas production using a fixed dome bioreactor is proposed. Fecal sludge from pit latrines and vegetable waste from the kitchen is proposed as the main feedstock. Biogas utilization in cooking and lighting is recommended and reuse of the slurry and the effluent in the agriculture. Post treatment is recommended in drying beds for the slurry and a polishing bed with reeds for the effluent.

The samples used in the biogas lab experiment were black water (7.95 gr TS/l and 6.47 gr VS/l), kitchen waste (initially 168.52 gr TS/l and 150.33gr VS/l, later 49.97 gr TS/l and 44.39 gr VS/l after dilution) and a mixture of both (52.86 gr TS/l and 45.61 gr/VS/l). The incubation period was 30 days. The presented results represent the biogas production of the mixed sample and inoculum substrates. The reason is that the inoculum used was not fully degraded and consequently a substantial fraction of the produced biogas is attributed to it. The black water sample produced 371.64 ml biogas/gr VS added with 79.46% methane content. The kitchen waste and the mixture samples were inhibited because of high organic loading and pH drop.

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Abbreviations

ABR: anaerobic baffled reactor
ACTS: African Center for Technology Studies
AD: anaerobic digestion
AF: anaerobic filter
BMP: biochemical methane potential
C:N: carbon to nitrogen ratio
CHP: combined heat and power

COD: chemical oxygen demand

DM: dry matter

GIZ: Gesellschaft fur Internationale Zusammenarbeit

HRT: hydraulic retention time

MCF: Mulli’s Children Family

MDGs: Millennium Development Goals

SRT: solid retention time

TS: total solids

UASB: up flow sludge blanket

VFA: volatile fatty acids

VS: volatile solids

Chapter 1 : Introduction

1.1. Background

Energy poverty poses as one of the greatest challenges in global scale, especially for developing countries. Overcoming the problem is directly linked with achieving the Millennium Development Goals (MDGs) (Energy 2005). Energy poverty is also directly related with gender issues. In rural areas, women and young girls are typically responsible for providing the household with biomass fuel (figure 1.1), having to walk long distances for several hours a day to collect heavy fuelwood loads, causing health problems and stress to them and restricting them from other important productive, social and educational activities (Clancy, Skutsch et al. 2002). Additionally, the indoor burning of traditional biomass fuels, such as firewood, coal and cow dung, causes emission of harmful fumes that are implicated with health issues that range from mild respiratory illnesses to lung cancer, with infants, children and pregnant women being the most affected (Ezzati 2005).

Figure 1.1. A Kenyan woman carrying firewood at the Kibera slum *Photo: I. Georgiadis*

A critical factor for rural communities in order to adapt to climate change effects is to develop human and financial capacity through the delivery of energy that is both affordable and reliable (Casillas and Kammen 2010). The potential environmental and

economic benefits of bioenergy, in the form of biomass, biodiesel, bioethanol and biogas, have been gaining worldwide popularity and it has been suggested that if developing economies actively invest in the spreading of this kind of renewable energy technologies the benefits will include sustainable energy production, food security and improved livelihoods (Msangi, Sulser et al. 2007). Namely biogas technology has the potential to improve sanitation, reduce greenhouse gas emissions, provide nutrient rich organic fertilizer and replace traditional fuels in cooking, thus improving indoor living conditions and reducing deforestation, while being financially attractive, in the sense that the investment costs can be paid back in a short term, when good design and operation and maintenance conditions are applied (Brown 2006).

1.2. Scope

The present thesis is part of a project that took place during February 2013 at Mulli's Children Family (MCF) farm at Yatta, Kenya and was ordered to the Energy Garden, Norway by MCF and the Kenyan branch of Norwegian Church Aid. The project's objectives were to map the energy needs of MCF and the available resources in order to estimate the renewable energy potential. Along with the author of this thesis, whose focus was on biogas production potential, two master students of the Department of Mathematical Sciences and Technology of UMB took part, also as part of their master thesis: Andreas Tutturen, who focused on biomass potential, and Ragnhild Tjore, who focused on solar energy potential. In this respect, the focus of this thesis will be more on the aspect of energy production, in the form of biogas, rather than treatment efficiency.

Early enough, it was obvious that the people of MCF were interested in how much they can save, in financial and energy terms. This question translates to how much is the methane potential of the available substrates. However, this was difficult to occur on site. So, additionally to the resource mapping, lab experiments were conducted.

1.3. Objectives

A small review of the theory, the technology and the regime regarding anaerobic digestion, biogas production and utilization and byproducts utilization will be presented. The objective of this part is to provide the theoretical background on the subject, both for the case study and the lab experiment chapters and highlight different aspects that might be a barrier in real life situations.

The objectives of the case study part are the mapping of the available resources for biogas production at MCF's farm at Yatta, the estimation of their methane potential and potential energy and financial benefits and ultimately the proposal of a small scale anaerobic digestion system with biogas production being in focus, that can possibly become part of their on-site waste and wastewater management.

The objectives of the lab experiment part are to demonstrate a simple experimental procedure through which the biogas and methane potential of different substrates can be estimated and acquire numbers that can be used as a reference.

Chapter 2 : Theory

2.1. Anaerobic digestion process and microbiology

Anaerobic digestion is based on a series of complex interconnected processes that can generally be divided into biological processes carried out by microorganisms in the absence of oxygen and physicochemical reactions. Generally speaking, the action that takes place is the conversion of large organic molecules to fully reduced methane and fully oxidized carbon dioxide in the absence of oxygen. A simplified version of the reaction can be described by the following equation (Evans 2001):

$$\text{Organic material} \rightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S$$

The biological process involves three basic steps: a) hydrolysis, b) fermentation and c) methanogenesis. Each step is briefly explained below:

a) Hydrolysis: the participating bacteria cannot directly process the organic substrate input. The particulate organic material, that is consisted of proteins, carbohydrates and lipids, has first to be broken down into soluble polymers or monomers, like amino acids, sugars and fatty acids (Gujer and Zehnder 1983). This process is called hydrolysis. The hydrolytic reactions that take place are carried out by extracellular enzymes produced by bacteria, such as cellulases, amylases and proteases (Grady Jr, Daigger et al. 2011). According to Zeeman and Sanders (2001) hydrolysis is usually the rate-limiting step in the process of anaerobic digestion of particulate organic substrates (Zeeman and Sanders 2001). The reason is that the bacteria responsible for the liquefaction of complex compounds, mostly cellulose, are operating at a very slow rate at this step, compared to the following ones, and are highly dependent on digester conditions, such as substrate availability, bacterial population density, temperature and pH (Evans 2001).

b) Fermentation: also referred as acidogenesis. During this step the hydrolyzed products, the amino acids, sugars and some fatty acids are being further degraded into even simpler molecules by bacteria. The final products of the fermentation process are

primarily acetic acid, hydrogen and carbon dioxide and secondarily propionic and butyric acids, which go through a subsequent fermentation producing more hydrogen, CO_2 and acetic acid (Grady Jr, Daigger et al. 2011). The pH falls as the concentration of these compounds increase.

c) Methanogenesis: the final step of anaerobic digestion. The microorganisms that are responsible for the production of methane belong to the archaea. They are commonly referred as methanogens and are obligate anaerobes. There are two groups of methanogens that are involved in utilizing the final product of the fermentation stage (Grady Jr, Daigger et al. 2011). The first group, called acetoclastic methanogens, splits acetate into CH_4 and CO_2 and the second group, called hydrogen-utilizing methanogens, utilizes H_2 as the electron donor and CO_2 as the electron acceptor in order to produce methane (Metcalf and Eddy 2003).

The sequence of the processes described above can be summarized in the following figure 2.1.

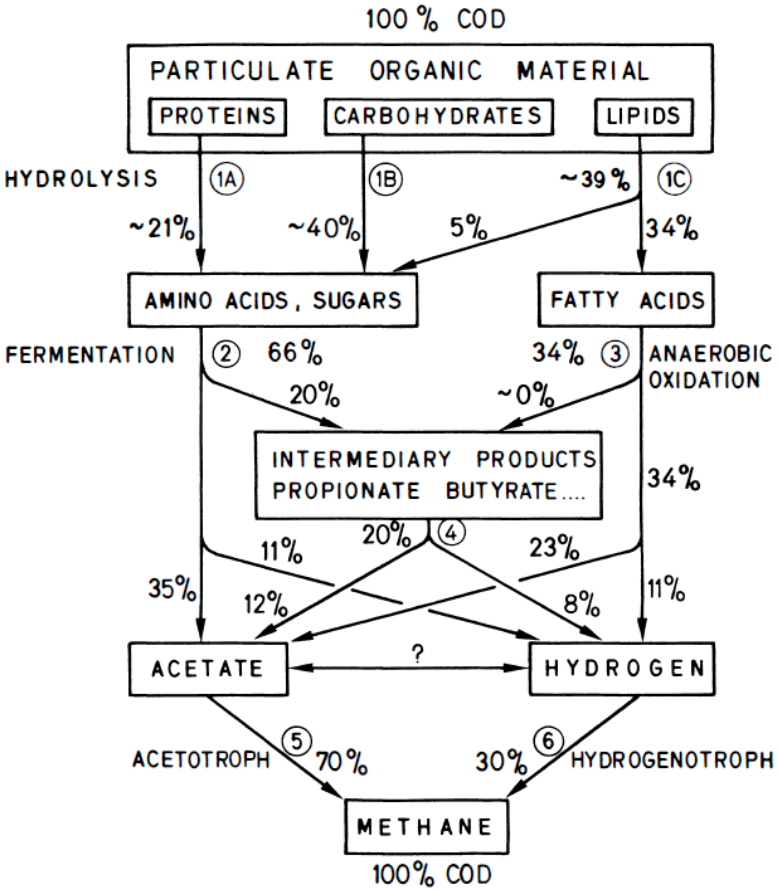

Figure 2.1. Anaerobic digestion process (Gujer and Zehnder 1983).

The physicochemical reactions that take place during the process are considered those not arbitrated by microorganisms. These reactions include liquid-liquid reactions, gas-liquid exchanges and liquid-solid transformations and should be taken into consideration when modeling the anaerobic systems (Batstone, Keller et al. 2002).

2.2. Parameters influencing anaerobic digestion and biogas production

The numerous biological processes that take place during AD are governed to a very large extent by the conditions inside and outside the bioreactor. In order to maintain the appropriate conditions for bacterial activity and to optimize methane production, which in most of the cases is the ultimate goal, there are some operational parameters that need to be taken care off.

These parameters, when neglected, can cause instability on the overall process and limit the potential biogas yield or lower the methane content of the final gaseous product. For that reason they need to be taken into consideration throughout the bioreactor selection and design process, the choice of the substrate and operation and maintenance.

2.2.1. Temperature

Bioreactors are generally divided into two groups according to the temperature they operate. These are mesophilic (30^{o}C to 35^{o}C) and thermophilic (50^{o}C to 60^{o}C). This has to do with the fact that most of the methaogens are active in these temperature ranges, though mesophilic AD is the most widely used, since most of the methanogens are mesophiles (Deublein and Steinhauser 2011).

Problems occur in several cases. Temperature in the range between 40^{o}C and 50^{o}C inhibits the activity of methanogens and the performance of the bioreactor starts to deteriorate at around 42^{o}C, that represents the transition from mesophilic to thermophilic organisms (Gerardi 2003). Also, when temperature falls below 32^{o}C methanogens start to operate at a slower rate, while the acid forming bacteria continue with the same rate, leading to increase of acidity in the digester (Gerardi 2003). Sudden temperature changes affect microbial growth rates, as well as fatty acids concentration. A raise in temperature results in higher metabolic rate of the microorganisms but also in a higher concentration of volatile fatty acids (Chen, Cheng et al. 2008).

Generally, mesophilic temperatures, more specifically approximately 35^{o}C, are considered as the optimal digester temperatures and it comes as no surprise that most cases in the literature, in relation to enhancement of biogas production, are aimed at increasing and maintaining the digester temperature to the mesophilic range (Sreekrishnan, Kohli et al. 2004).

Methane production is higher and faster in digesters operating at thermophilic temperature ranges, because the volatile solids are destroyed at a greater rate (Gerardi 2003). Thermophilic AD is a more difficult process, since the thermophilic methanogens that take part are highly sensitive to changes, and occurs more usually in industries and in wastewater treatment plants that have the capacity to heat the substrate up to the desired temperature range (Gerardi 2003).

Biogas production under psychrophilic conditions, in the range of 15C^{o} to 20C^{o} and lower, is regarded to be quite challenging, in technical and financial terms. However it is plausible. In most cases in literature, psychrophilic methane production has been carried out by mesophilic methanogen species (termed psychotrophs) that can be acclimatized and operate at lower temperatures and can adapt to thermal changes in of their environment (Kashyap, Dadhich et al. 2003). Usually, biogas production is very slow and measures are taken in order to raise digester temperature to mesophilic range.

2.2.2. Alkalinity and pH

These two interdependent parameters need to be adjusted in order to keep the chemical conditions in the bioreactor at an optimal state.

Alkalinity serves as buffer that prevents rapid pH change. The enzymatic activity of bacteria is influenced by pH. The activity of acid forming bacteria occurs above pH 5. For the methanogenic activity pH under 6.2 becomes a strong limiting factor, while the optimal range is 6.8 to 7.2 (Gerardi 2003). The production of volatile fatty acids will initially cause a decrease of pH, and then the methanogens will consume the VFAs, producing alkalinity that will consequently raise and eventually stabilize the pH in the bioreactor. In a properly operating bioreactor pH at this range is achieved as volatile acids are converted to CH_4 and CO_2 (Gerardi 2003).

The pH range of 6.8 to 7.2 is satisfactory, though pH at the range of 7 to 7.2 is the best for the efficiency of the anaerobic digestion process. A decrease in alkalinity usually precedes a rapid change in pH. Changes in alkalinity and pH are caused by the substrate feed or the production of acidic and alkali compounds, such as organic acids and ammonium ions, respectively, during the degradation of organic compounds in the digester (Gerardi 2003).

To maintain stable pH, a high level of alkalinity is required. Adding alkalinity, e.g. in the form of $CaCO_3$, may be needed to raise and maintain an acceptable pH with high gas phase CO_2 concentration. The level of alkalinity in the substrate, e.g. in municipal wastewater, is not always appropriate, but may be generated in some cases by the degradation of proteins and amino acids (Metcalf and Eddy 2003).

2.2.3. Ammonia

Nitrogen inhibits the AD process in the form of ammonia (NH_3). Ammonia is formed through the biological process of the anaerobic degradation of nitrogen compounds. NH_3, especially in its free form, in high concentration affects methanogens in a negative way and thus has an inhibitory role (Deublein and Steinhauser 2011).

Ammonia inhibition is directly related with pH and temperature. Increasing pH and temperature leads to large production of ammonia. However, ammonia inhibition results in an increase of the VFA concentration, which has the subsequent effect of a decrease in pH. This will partly counteract the inhibitory effect of NH_3 with a decrease in the free ammonia concentration (Al Seadi 2008).

The population of the methanogens can be inhibited at free ammonia concentrations of >50mg/l, though it can be acclimated and then is able to withstand some hundred milligrams per liter of free ammonia, before the whole process gets endangered due to ammonia toxicity (Gerardi 2003).

2.2.4. Hydrogen

The production of hydrogen (H_2) during anaerobic oxidation is essential for the overall AD process. The reason is that H_2 is the main electron donor in the methane formation process and makes the acetic acid the major soluble organic substance produced during acidogenesis (Grady Jr, Daigger et al. 2011). The dependency of the methanogenic bacteria that utilize H_2 on the acetogenic bacteria that produce H_2 implies that the concentration of H_2 has to be balanced. On the one hand it should not be too low, so that there is enough H_2 for the methanogens to use or too high, so that the acetogenic bacteria will continue producing hydrogen (Deublein and Steinhauser 2011). In this respect, in order to avoid inhibition of the metabolism of the acetogenic bacteria, a low partial pressure of hydrogen has to be maintained (Weiland 2010).

2.2.5. C:N ratio

The microorganisms involved in AD require a small yet sufficient enough amount of nutrients in order to grow their biomass (Metcalf and Eddy 2003). Nitrogen (N) is an important nutrient for the process in the respect that it enables the bacteria to produce the appropriate enzymes to utilize carbon (C). There must be a balance between these two elements. This balance is usually expressed as C:N ratio. When C:N is too high the bacteria cannot utilize carbon, while if it is too low then the process can be

inhibited (Stafford, Hawkes et al. 1981). Generally the optimum C:N ratio is considered to be between 20:1 to 30:1.

2.2.6. Organic loading rate

Organic loading rate is an important digester design parameter that determines the amount of substrate per unit volume that will be put into the digester in order to be stabilized and the part of it that ultimately will be converted into gas. The effectiveness of the AD process is also determined by the loading rate. Organic loading rate refers to the amount of organic matter that enters the digester and is usually expressed as kg volatile solids (VS) VS/m^3 reactor volume per day, or alternatively as COD per liter (Evans 2001).

A too high loading rate has an overloading effect that translates into an increased VFA production, decreased gas production and disproportional raise in the CO_2 fraction of the biogas (Stafford, Hawkes et al. 1981). In the case that solids in the substrate exceed 12%, gas production can be reduced. For this reason, that has to do with the financial viability of the process, the content of solids should not exceed 30%, because low wetness can result to slow cell growth, the material transfer inside the substrate start to inhibit the process and mixing and pumping of the biomass becomes very difficult. On the other hand with too low loading, even though the process works, it is not economically sound because too much water is being consumed (Deublein and Steinhauser 2011).

2.2.7. Retention time

In an anaerobic digester there are two types of retentions times that are significant design and process parameters. The one is solid retention time (SRT) and refers to the average time spent by the bacteria (solids) in the bioreactor. The other one is the hydraulic retention time (HRT) and refers to the time that the influent is in the bioreactor. SRT is the same with HRT when there is no recycling of digested sludge.

In general, SRT higher than 20 days is needed (Metcalf and Eddy 2003). Less time will force large amounts of methanogens to be washed out the digester with the effluent, thus damaging the AD process, which makes SRT a more significant parameter than HRT (Gerardi 2003).

High SRT has multiple positive effects on the overall AD process and the digester design: higher organic load removal capacity, reduced digester volume, shock loads resistance and microorganism acclimation to toxic compounds. It can be achieved either by increasing the volume of the digester or by increasing the bacterial population (Gerardi 2003).

2.2.8. Inhibitors

Many undesirable organic and inorganic substances occur in the various substrates. These substances, referred as inhibitors, harm the AD process. Inhibitors can have a negative effect on the enzymatic activity of the bacteria in the bioreactor. The level of effect that these substances have on the process varies greatly in literature. The reason is that AD is a complex process and the inhibition effect is influenced by mechanisms such as antagonism, synergism, acclimation, and complexing (Chen, Cheng et al. 2008). Ammonia, sulfide and heavy metals are among the most common inhibitory substances. The inhibitory effect of ammonia has already been discussed above.

Sulfide, in the form of sulfate, is known to inhibit the process. In a bioreactor, sulfate is being reduced by the sulfate reducing bacteria that participate in the process. This affects the AD process in two stages. There is the primary inhibition stage, during which methanogenic bacteria are suppressed because of the competition between organic and inorganic substrates produced by the sulfate reducing bacteria. The secondary stage has to do with the toxic effect of sulfide to various bacteria groups of the AD process (Chen, Cheng et al. 2008).

Heavy metals present in the substrate can have an inhibitory or toxic effect on the AD process. Heavy metals are not biodegradable, so they accumulate in the bioreactor. At higher concentrations, heavy metals can avert or completely impair the enzyme

function of some bacteria groups by binding with certain groups on protein molecules or by replacing naturally occurring metals in enzyme prosthetic groups (Chen, Cheng et al. 2008). The way heavy metals inhibit the process is primarily nonspecific, reversible and noncompetitive. More specifically, the inhibitor binds reversibly with either the enzyme or the enzyme substrate complex (Oleszkiewicz and Sharma 1990).

2.3. Substrates for biogas production

According to the anaerobic digestion fundamentals that were briefly described above, any type of biomass that contains carbohydrates, proteins, fats cellulose and hemicellulose can be used as substrate. However, not every biomass that contains these appropriate substances can be used as substrate. Substrates are significantly related to the parameters that govern and influence the optimal performance of the AD process. A list of general points that should be considered can be seen in the table 2.1 below (Deublein and Steinhauser 2011).

Table 2-1. General points for selecting appropriate substrates (Deublein and Steinhauser 2011).

The concentration of organic material should be as indicated by the fermentation process.	The bacteria involved in the three stages of AD process utilize the organic material that is in the form of carbohydrates, proteins, fats cellulose and hemicellulose.
The potential for biogas production should be the highest possible.	The parameters, like temperature, pH, C:N ratio among others, that optimize the biogas production.
Pathogens and other malign organisms in the substrate should be disabled prior the fermentation process.	AD process alone, especially in the mesophilic temperature range, is not very effective as a hygiene barrier.
Inhibiting substances and indigestible material that have the potential to slow down and destabilize the AD process should be kept in a minimum concentration.	Chemicals that inhibit, harm or inactivate the methanogenic bacteria should be avoided. Also, material like wood and plastic that decompose at an extremely slow rate should be at a least possible concentration.
The composition of the final gaseous product should be appropriate for further use.	The methane fraction of the produced biogas should be as high as possible and the gas should be stripped from hydrogen sulphide that has a bad smell and can damage the internals of an engine.
The composition of the residual digested material should be safe and have a nutritional value in order to be reused in agriculture or other purposes.	The final remaining product rich in nitrogen and phosphorous and should be used as fertilizer. However, there are strict rules that should be followed prior to application in the field.

Considering the aforementioned points, waste and wastewater of a diverse variety of origin (animal, agricultural, industrial, municipal and domestic) can be considered appropriate substrates for biogas production. Academic literature on the subject is vast.

Traditionally anaerobic digestion has been used for the treatment of animal manure and sewage sludge produced during water and wastewater treatment processes. The current trend, for agricultural biogas plants, is the use of pig and chicken manure as feedstock, usually with the addition of co-substrates such as harvest residues, organic waste from industrial or agricultural activities, food waste, municipal biowaste and energy crops (Weiland 2010).

Co-digestion of different substrates is an attractive option. Co-substrates assist the process by adjusting parameters, such as pH, C:N ratio, moisture content, and raising the content of organic material, thus resulting to higher biogas yield. Additionally, handling and mixing of difficult to handle substrates can be made easier. The disadvantages of co-digestion mainly are costs that are generated from slurry transport and problems related with coordinating the policies that apply for the different types of waste (Mata-Alvarez, Mace et al. 2000).

2.4. Bioreactor types.

Bioreactors come in many types that vary in design, size, settings, performance, operating parameters and complexity. Some of the bioreactor types that are appropriate for small scale on site treatment of organic waste and wastewater and biogas production are shortly presented and described below.

2.4.1. Anaerobic Baffled Reactor (ABR)

The ABR is a gas tight septic tank (figure 2.2) that consists of several chambers connected in series. Wastewater flows in up-stream and then down and up from one compartment to the next. The activated sludge, which is located on the bottom of each

chamber, is mixed by the flowing wastewater (Foxon, Pillay et al. 2007). The bacteria within the reactor gently rise and settle due to flow characteristics and the gas that is produced. This way the organic pollutants get in touch with the bacteria and decompose (Barber and Stuckey 1999).

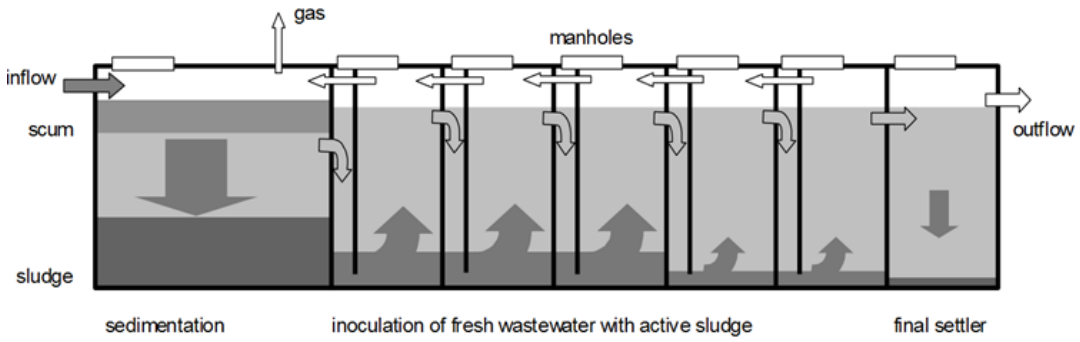

Figure 2.2. ABR (SANIMAS 2005).

The advantage of ABR is that it is a simple design with no moving parts and does not require mechanical mixing. Consequently the capital cost and the operation and maintenance cost is low (Barber and Stuckey 1999).

2.4.2. Anaerobic Filter (AF)

The anaerobic filter (AF), also known as fixed bed or fixed film reactor, has a similar design with ABR (figure 2.3). The way it differs is that there is biofilm attached to the filter media that enables the treatment of non-settable and dissolved solids (SANIMAS 2005). When the biofilm gets too thick, it has to be removed by backwashing in order to avoid clogging. As a result, AF is usually operated up-flow, because the risk of washing out active bacteria is lower this way (Sasse 1998). In the case that the filter media can be locally acquired, the construction costs are comparable to those of an ABR. The operation is a bit more complicated because of the required backwash.

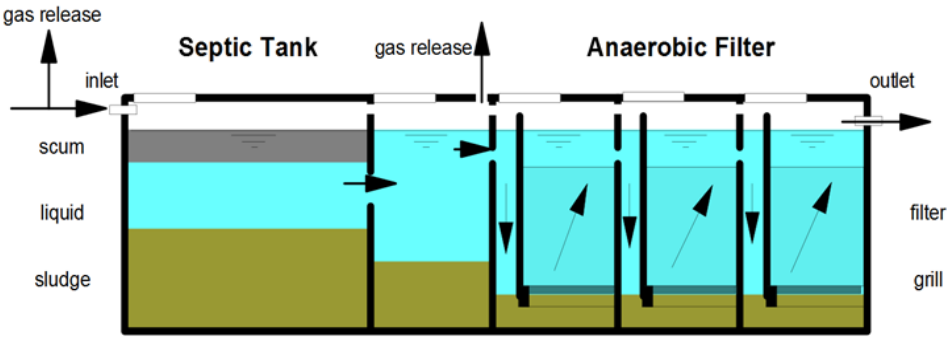

Figure 2.3. AF (Sasse 1998).

2.4.3. Upflow Anaerobic Sludge Blanket (UASB) reactor

The incoming wastewater is distributed from the bottom of the UASB reactor and flows upwards through the sludge blanket. Along with the influent distribution system, the other important parts of an UASB reactor are the gas-solids and the effluent outlet design, as well as the gas collection system (Metcalf and Eddy 2003). Some common modifications of the basic design can include a settling tank and an internal packing material on the top of the reactor. This modifications (figure 2.4) aim to more efficient solids capture in the system and prevent reactor solids to escape due to process disturbances (Metcalf and Eddy 2003).

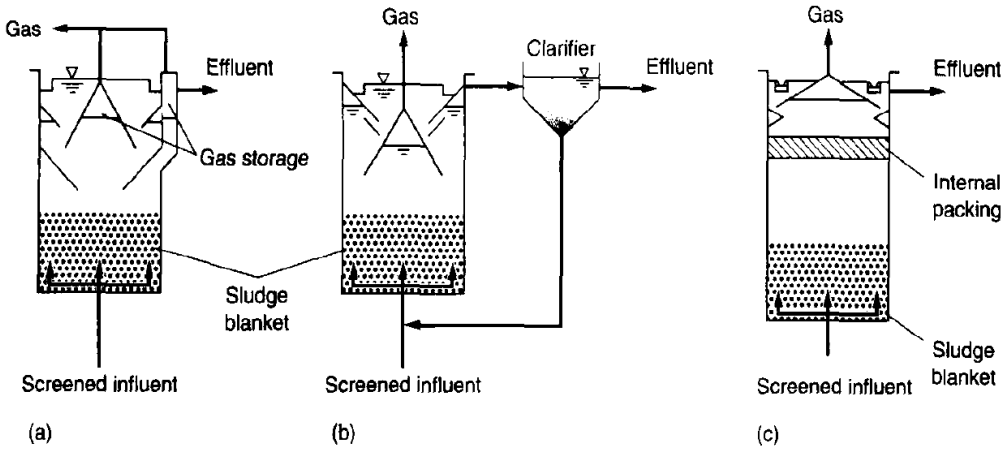

Figure 2.4. a) UASB reactor original design, b) UASB reactor with sedimentation tank and sludge recycle and c) UASB reactor with internal packing for fixed film attached growth (Metcalf and Eddy 2003).

2.4.4. Fixed dome digester

The fixed dome digester (figure 2.5), commonly known as the "Chinese model", is a closed dome-shaped digester with a still gas holder and a displacement pit. It is usually constructed underground in order to be protected and for space saving reasons (Kossmann, Poenits et al. 1997). There are no movable parts or parts that can be subjected to erosion, so the construction costs are low and the lifetime of the digester is quite extended (U.N. 1984).

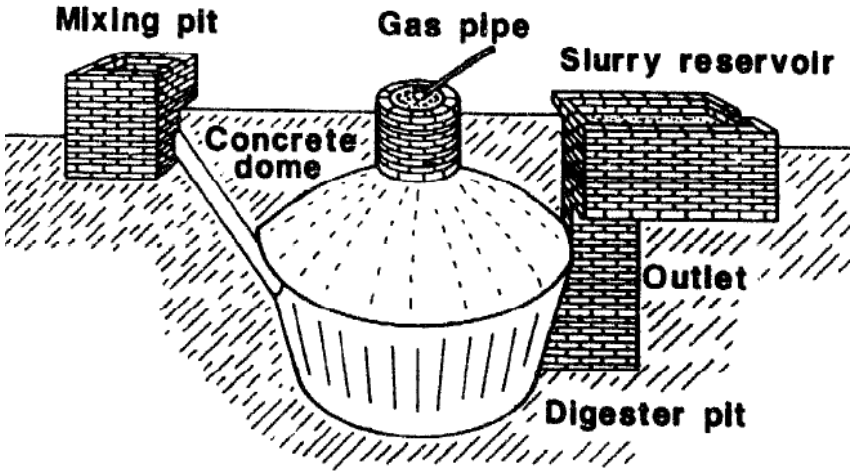

Figure 2.5. Fixed dome digester (Fulford 1988).

The dome structure of the digester requires experienced masons in order to achieve air tightness. The costs depend on whether or not the construction material can be locally acquired or need to be transported. The overall construction is labor intensive and thus can create local job opportunities (Kossmann, Poenits et al. 1997). The produced biogas is being stored on the top part of the fixed dome.

The main problem with fixed dome plants is that cracks can occur on the airtight dome due to gas pressure, allowing gas to escape (U.N. 1984).

2.4.5. Floating-drum digester

A floating-drum digester is similar in design with the fixed dome digester (figure 2.6). The key difference is in the way that the top gas holding part of the plant is

constructed. It is a moving, floating gas-holder, or drum made of steel, which floats either directly in the substrate or in a separate water jacket (Kossmann, Poenits et al. 1997).

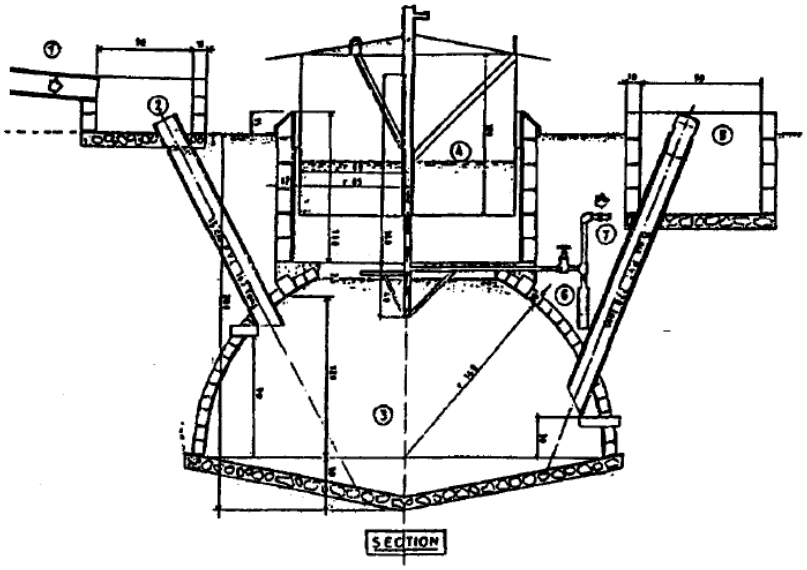

Figure 2.6. Floating-drum digester (Laichena and Wafula 1997).

The construction cost of the steel drum is relatively high; representing usually 35 to 40% of the investment cost and requires experienced masons (U.N. 1984). Moreover, in time it can rust and therefore requires regular maintenance. The advantage of the moving gas holder is that it can be lifted, facilitating this way the cleaning of the scum from the digester chamber, it can be rotated, providing this way limited stirring of the substrate and offers relatively constant gas pressure (U.N. 1984).

2.4.6. Plastic balloon digester

A balloon digester is actually a big bag made out of plastic or rubber that is air tightly sealed and basically serves both as digester and gas holder (figure 2.7). The balloon digester is usually prefabricated and easy to transport. As a consequence the investment costs are very low (Kossmann, Poenits et al. 1997). Balloon digesters are flexible and are suitable when there is bedrock or when the groundwater table is very

high. The disadvantage is that the plastic or rubber material can easily be damaged. Additionally, the material has to be weather resistant and UV proof (Kossmann, Poenits et al. 1997).

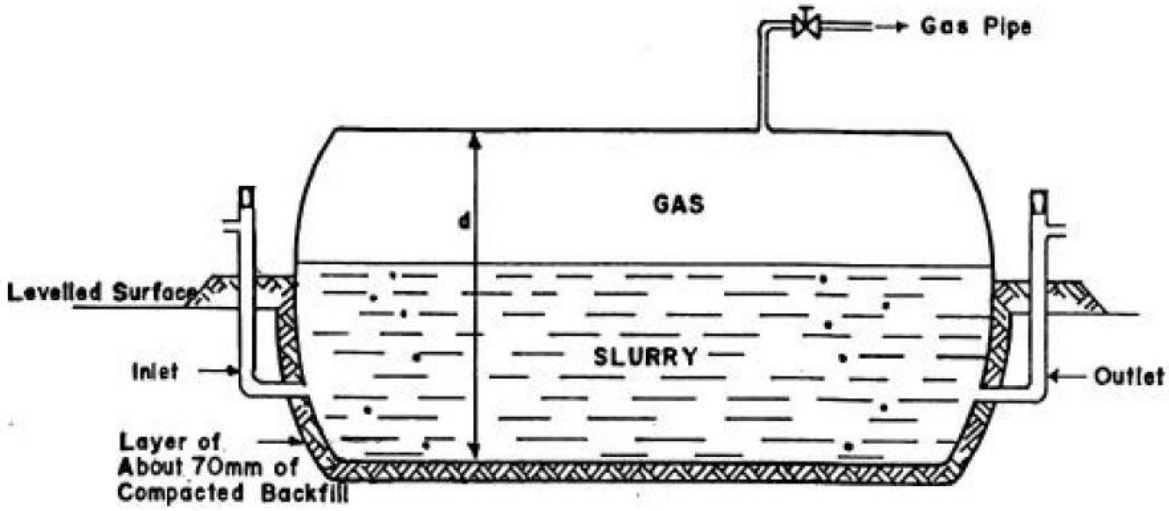

Figure 2.7. Plastic balloon digester (FAO 1996).

2.5. Biogas composition

Biogas is predominantly composed of methane (CH_4) and carbon dioxide (CO_2), with CH_4 concentration ranging from 60 to 70% and CO_2 from 40 to 30% depending on the feedstock and the AD process parameters and performance (Stafford, Hawkes et al. 1981). These two constituents are closely correlated (figure 2.8) and the ratio can be partially controlled depending on composition of the feedstock, retention time, mixing, wetness, temperature, pressure, decomposition and pretreatment (Deublein and Steinhauser 2011).

Along with CH_4 and CO_2, the other gases that are contained in biogas in minor concentrations are hydrogen (H_2), hydrogen sulphide (H_2S), nitrogen (N_2), ammonia (NH_3) and water in gas phase (H_2O) (table2.2) (Al Seadi 2008).

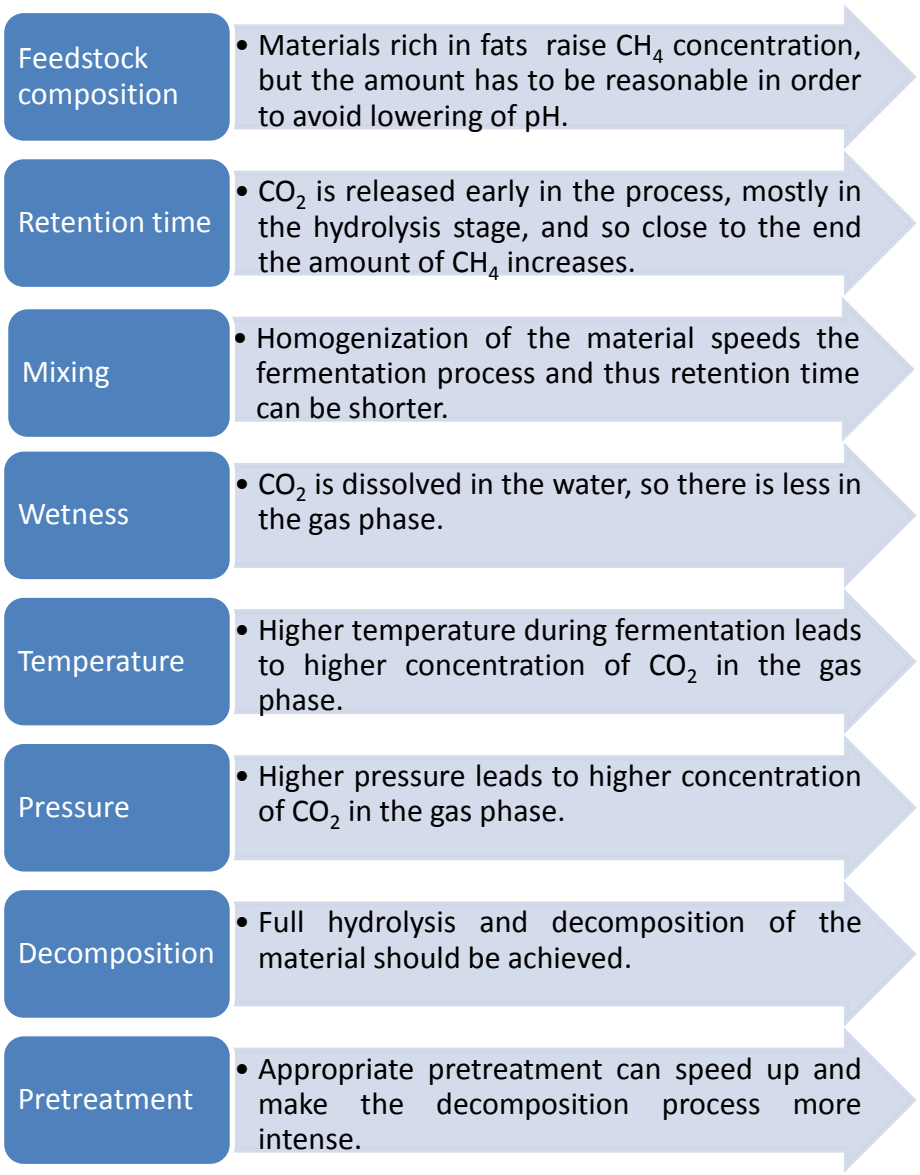

Figure 2.8. Methane and carbon dioxide during AD process (Deublein and Steinhauser 2011).

Table 2-2. Biogas composition (Al Seadi 2008).

Compound	Chemical symbol	Content (Vol.-%)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapour	H_2O	2 (20°C) -7 (40°C)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

2.6. Biochemical methane potential (BMP) assays

BMP assays are regarded as quick and inexpensive method for determining the rate of conversion of biomass and wastes to CH_4 and for estimating their CH_4 potential (Nallathambi Gunaseelan 1997).

Moody, Burns et al. (2009) describe the BMP assay as follows: First wastewater samples are inoculated with active anaerobic bacteria and then they are incubated for a period of 30 to 60 days usually at 35^{o}C. Several wastewater to inoculum sample ratios can be examined during one assay. Biogas production and CH_4 content of the samples are measured throughout the test, as well as a control containing only inoculum and water in order to determine CH_4 production resulting from the inoculum alone (Moody, Burns et al. 2009). The characteristics of the substrate used in the BMP assay that need to be analyzed are TS, VS, COD, nitrogen and phosphorous and the inoculum should be active and newly collected from an operating anaerobic reactor (Angelidaki, Alves et al. 2009).

The general outcomes expected when conducting BMP assays in brief are: a) to compare the extent and the rates of conversion of various substrates to CH_4, b) compare the BMP of different varieties or parts of the same substrate, c) examine the effect that different process parameters and conditions have on the BMP of the same substrate, d) to evaluate the effect that different pretreatment methods have on the BMP of the same substrate and e) to find out if there is a correlation between organic composition and the extent and rate of conversion to CH_4 (Chynoweth, Turick et al. 1993).

2.7. Biogas utilization

Biogas is a valuable gas that can be utilized in numerous ways. Biogas produced from big scale bioreactors, using animal manure and agricultural waste or energy crops, is more frequently used for heat production by direct combustion, combined heat and

power (CHP) generation, electricity production by fuel cells or micro-turbines, or as fuel for specially modified vehicles (Al Seadi 2008).

CHP generators are more widely used in biogas plants compared to fuel cells and micro-turbines, with a sum of electrical and thermal efficiency up to 85-90% with modern CHP generators and electrical efficiency alone up to 40% (Deublein and Steinhauser 2011). Biogas can also be fed into the grid and utilized as vehicle fuel, in an attempt to be used in a more energy efficient way throughout the year. These uses require polishing of the gas by removing all undesired gases, such as H_2S as well as CO_2 and the CH_4 concentration should be up to more than 95% (Weiland 2010).

Biogas produced from small scale or household level bioreactors is commonly utilized on site for heat production that can be used for water heating, in cooking, replacing traditional wood fuel and lighting, where electricity is not available.

Biogas cook stoves (figure 2.9) can be fed directly with gas or with bottled gas. The main components of the stove are the injector, the air/gas mixing chamber and the burner. The combustion of biogas is regulated by moving the injector into and out of the air/gas chamber, which regulates the amount of air that enters into the chamber (Itodo, Agyo et al. 2007). Improved biogas cook stove models have been developed with biogas consumption rating of 375 l/h and thermal efficiency rating of 60.10% (Kurchania, Panwar et al. 2011).

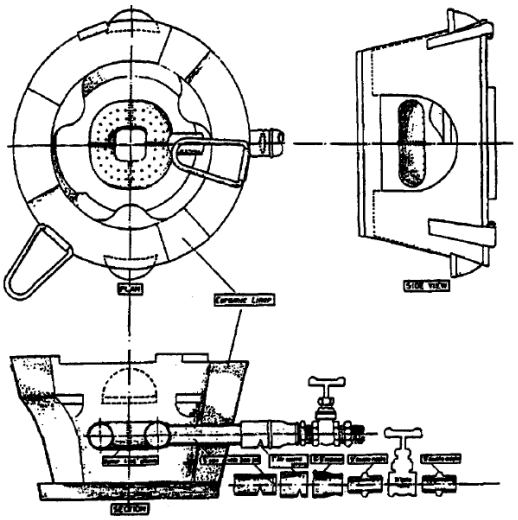

Figure 2.9. Biogas cook stove (Laichena and Wafula 1997).

A biogas lamp consists of a gas regulator, a venturi tube, a clay nozzle, a mantle and a gas globe (U.N. 1984). The mantle of a biogas lamp resembles a small net bag and a binding thread made of ceramic fiber thread is provided for tying it onto the ceramic head. A biogas lamp can give light equal to 60-75 watt electric bulb (Lam and Heegde 2007).

2.8. Biogas slurry utilization

A significant benefit of anaerobic digestion, next to energy production in the form of methane, is that the slurry, usually termed digestate, is a nutrient rich product that after appropriate treatment can have a great value as fertilizer. The anaerobic digestate can be applied on the fields with the same equipment used for liquid manure.

The following facts and advantages of biogas slurry have been validated: a) there is very little if any phosphorus (P) and potassium (K) loss during the process, b) small loss of nitrogen (N) occurs, however a percentage of the organic nitrogen in the substrate is transformed to an ammoniacal form (NH_3-N), that is more readily absorbable by plants, given that the slurry has not been dried too much, c) the percentage solids in the output digested slurry are lower than the input because part of it is broken down by bacteria, d) the volume of the fertilizer produced from a certain amount of dung, will be greater after treated through anaerobic digestion than through aerobic composting, assuming the same moisture content, e) there is less leaching of nutrients than in raw animal manure that is left to dry and consequently allow nitrogen to be lost due to volatilization (U.N. 1984).

Additionally, substances, such as volatile acids, phenol and phenol derivatives that cause persistent bad odor are reduced, so that the smell of the final product is improved not only in intensity but also in composition (Al Seadi 2008). It has been shown that up to 80% of the odors in the feedstock can be reduced (Weiland 2010).

Even though there is partial conversion of the organic nitrogen to NH_3-N, as mentioned earlier, the total nitrogen content in digestate remains the same as in the

feedstock. Some amount of NH_3-N, also referred as mineral nitrogen, is lost after application on the field due to ammonia volatilization, so the percentage of utilization is decreased (Lukehurst, Frost et al. 2010).

The biggest drawback is that anaerobic digestion, especially in the mesophilic range, does not have the full potential to serve as an adequate hygienic barrier; hence there are strict regulations that apply on the matter. Post treatment of the digestate and the effluent is required before reusing in agriculture. Generally, the survival of pathogenic organisms and their amount in the digestate and effluent depend on the type of the feedstock and how contaminated it is, the temperature and the retention time (U.N. 1984).

The main post treatment options that are currently used, not only for hygienic but also for environmental protection reasons, are: a) polishing ponds, b) overland flow or infiltration systems, c) activated sludge systems, d) submerged aerated bio filter, e) trickling filter systems, g) dissolved air flotation and finally h) constructed wetlands (Chernicharo 2006).

2.9. Treatment of organic wastewater with anaerobic digestion

Anaerobic processes are predominantly used for the treatment of concentrated organic waste and wastewater, though treatment of diluted wastewater has also been gaining ground the last decades (Metcalf and Eddy 2003).

2.9.1. Anaerobic treatment of wastewater compared to aerobic treatment

Compared to aerobic processes, anaerobic digestion has many advantages: a) it can be implemented with very low costs, because the technology is simple and the reactors can be relatively inexpensive, b) energy production takes place in the form of biogas, c) is very flexible regarding the place and the scale it can be applied, d) modern anaerobic wastewater treatment systems have small space requirements for high loading rates, e) lower and more stabilized excess sludge production, f) anaerobic

organisms can be preserved for long periods of time without losing much of their biological activity and g) with the combination of post treatment methods useful products like ammonia or sulfur can be recovered (Lettinga 1995). A more comprehensive presentation of the advantages and disadvantages of AD compared to aerobic processes is shown in the table 2.3 below.

Table 2-3. Advantages and disadvantages of AD (Metcalf and Eddy 2003).

Advantages	**Disadvantages**
Less energy required: energy use is balanced with energy production from biogas. Energy consumption during AD is closely related to the strength of the wastewater and depends on whether and how much the temperature of the substrate needs to be heated.	Longer start up time to develop necessary biomass inventory: May require months
Less biological sludge production: Sludge is being digested, so there is lower biomass production. Consequently sludge process and disposal cost is significantly less.	May require alkalinity addition: to maintain pH
Fewer nutrients required: Wastewater of industrial may lack the appropriate amount of nutrient content for aerobic treatment.	May require post treatment to meet discharge limits: effluent polishing is required for full hygienization. Temperature is not raised enough to deactivate pathogens
Energy production in the form of methane: Energy from biogas	Biological nitrogen and phosphorous removal is not possible
Smaller reactor volume required: AD processes have generally higher volumetric organic loads compared to aerobic processes.	Much more sensitive to the adverse effect of lower temperatures on reaction rates
Elimination of off-gas pollution: Greenhouse gases are kept in the closed airtight digester.	May be more susceptible to upsets due to toxic substances
Rapid response to substrate addition after long periods without feeding: Regeneration of the process is easily viable with the addition of an active substrate.	Potential for production of odors and corrosive gases

2.9.2. Biogas sanitation

Improved sanitation, complemented with energy production and nutrient recovery is made possible through anaerobic digestion or co-digestion of domestic wastewater and organic waste.

H.P. Mang and L. Zifu (2010) define biogas sanitation systems as ‘‘engineered systems designed and constructed to utilize biological processes which break down solids and soluble organics in the liquid by anaerobic bacterial action under exclusion of free oxygen in treating organically loaded sludge, excreta or wastewater’’ (Mang and Li 2010). Biogas sanitation can be regarded as an ecological sanitation technique, since feces and other solid organic waste are stabilized through the anaerobic treatment, energy production, in the form of methane takes place and the end product can serve as a nutrient rich fertilizer and soil conditioner, after appropriate hygienization (Werner, Bracken et al. 2003).

Source separation, in addition with using water saving toilets, like low flush or vacuum toilets, can enhance the positive outcomes of decentralized on-site anaerobic treatment of domestic sewage and other organic household waste, mainly kitchen refuse . The rationale behind source separation is to isolate the concentrated waste (black water, kitchen refuse) that contain the larger amount of organic pollution and the pathogens from the less concentrated waste (grey water, rain water) (figure 2.10) (Kujawa-Roeleveld and Zeeman 2006).

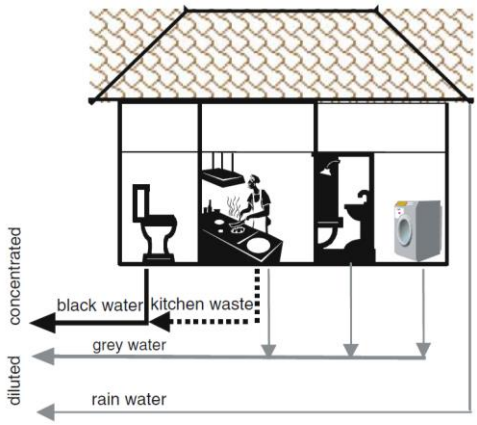

Figure 2.10. Source separation of domestic waste and wastewater (Kujawa-Roeleveld and Zeeman 2006).

The benefits include less dilution of the wastewater that needs anaerobic treatment, thus reducing the required bioreactor volume, and easier recovery of the nutrients and organic matter that are contained in the feces and urine (figure 2.12) (Vinnerås 2001).

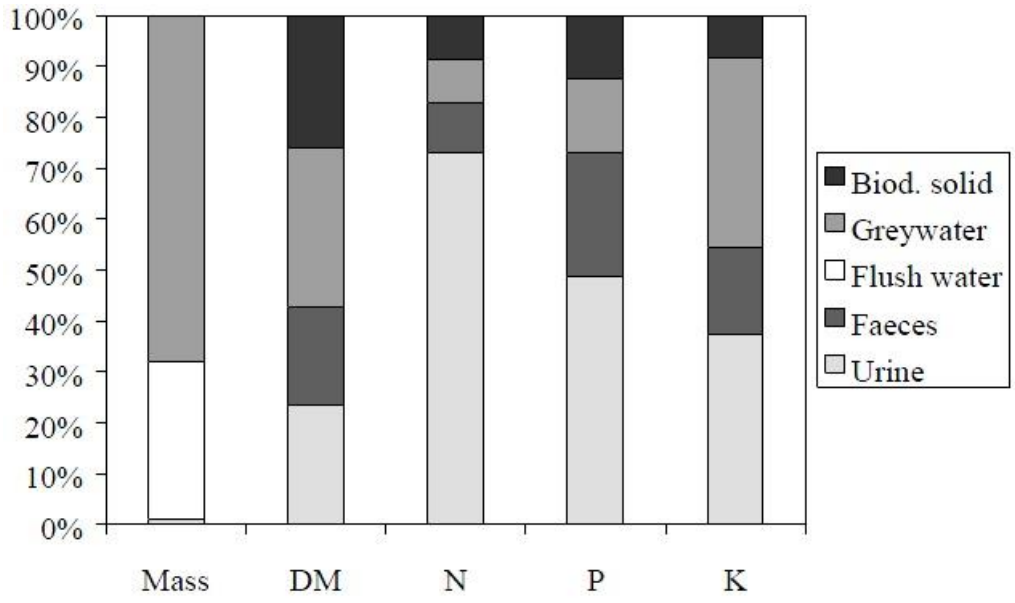

Figure 2.11. Nutrients and organic matter distribution among the different domestic wastewater fractions (Vinnerås 2001).

The main disadvantage is, as already mentioned, that mesophilic anaerobic digestion doesn't fully deactivate the pathogens that are present in the domestic sewage and post treatment of the effluent is required before discharge or reuse in agriculture.

Chapter 3 : MCF Yatta - Mapping of the available resources for biogas production

3.1. Biogas in Kenya

Biogas production in Kenya has been problematic for many years because of various reasons, including inappropriate design, construction and maintenance, water unavailability, substrate produced far away from the plant and needed to be transported, labor-intensive operation and poor social acceptability (Day, Chen et al. 1990).

In 1983 the Kenyan Ministry of Energy launched a campaign for the promotion of biogas production and utilization under the Kenyan Special Energy Program (SEP) and with the assistance of the German Gesellschaft fur Internationale Zusammenarbeit (GIZ) the ministry offered training programs for biogas plant builders. Consequently there was a raise in the numbers of installed biogas plants and by 1997 the number exceeded 500 all over the country (Laichena and Wafula 1997).

In more recent years, the Kenyan government has actively put biogas in the national energy agenda. Their intentions are to a) raise awareness regarding the benefits and potential of biogas technology, b) promote research, development and demonstration of the appropriate technologies, c) facilitate local construction of biogas reactors and equipment by introducing rebates and waivers, d) initiate training programs in institutions such village polytechnics on biogas installation, operation and maintenance skills and e) develop guidelines for registration and regulation of biogas contractors/technicians (Anonymous 2012a).

Additionally, the government is involved in the “Biogas for Better Life” program, which is an Africa-wide initiative that offers investment and business opportunities to scale up household biogas technology, and link it with achieving Millennium Development Goals connected with sanitation, gender, and livelihoods (Pandey, Subedi et al. 2007). The aim is to provide 2 million households in Africa with biogas

digesters by 2020. A feasibility study carried out under this initiative showed that it is possible to construct 6,500 biogas digesters in Kenya every 5 years and the government's intention is to construct 10000 bioreactors until 2030 (Anonymous 2012a).

The Kenyan Ministry of Energy has also issued a feed in tariff instrument for the promotion of the generation of electricity from renewable energy sources including electricity generated from biogas. For biogas projects with capacity from 0.2 up to 10 MW the standard fit in tariff is 0.1 US$ / kWh and it applies for 20 years from the date of the first commissioning of the biogas plant (Anonymous 2012b).

In 2009 a study from the GIZ mapped and identified the theoretical biogas of agro-industrial wastes for commercial scale biogas generation (table 3.1), as well as biogas potentials from wastewaters (table 3.2) in Kenya, which were published in a report (Fischer, Schmidt et al. 2010).

Some of the national organizations that take action in the field of biogas promotion are the Kenya National Federation of Agricultural Producers (KENFAP), the Kenya National Domestic Biogas Program (KENDBIP), Africa Biogas Partnership Program (ABPP) and National Environment Management Authority – Kenya (NEMA).

Responsible for the promotion and distribution of the technology are Kenyan governmental agencies such as Special Energy Programme (SEP) - Kenya and collaborating partners, Ministry of Energy and Regional Development (MOERD), Ministry of Livestock Development (MOLD), Kenya Industrial Estates (KIE) and private sector organizations such as Tunnel Technology Limited (TTL), Biogas Africa, Kentainers Limited, SEP trainees and individual entrepreneurs, the Christian Intermediate Technology Centre (CITC) and Kenya Wood fuel and Agroforestry Programme (KWAP) (Gitonga 1997).

Table 3-1. Data on biogas potentials from solid substrates (Fischer, Schmidt et al. 2010).

	Unit		Coffee pulp	Cut flowers wastes	Tea wastes	Sisal pulp	Old sisal plants	Sugar filter cake	Pineapple solid wastes	MSW Nairobi	Pig manure	Chicken manure	Vegetable waste
Amount of fresh waste	[tons/a]		110,295	27,358	9,640	615,050	120,000	192,705	75,000	996,450	10,920	82,125	798
		min	16.23%	21.84%	65.00%	9.00%	25.00%	20.00%	14.00%	30.00%	20.00%	18.00%	5.00%
		max	22.90%	32.76%	91.80%	14.30%	33.00%	30.00%	16.00%	60.00%	25.00%	32.00%	20.00%
DM content	[%FM]	average	19.57%	27.30%	78.40%	11.65%	29.00%	25.00%	15.00%	45.00%	22.50%	25.00%	12.50%
		min	92.80%	90.45%	95.00%	82.30%	90.00%	70.00%	95.00%	50.00%	75.00%	63.00%	76.00%
		max	92.80%	94.15%	98.00%	87.50%	96.00%	70.00%	97.00%	70.00%	90.00%	83.00%	90.00%
VS content	[%DM]	average	92.80%	92.30%	96.50%	84.90%	93.00%	70.00%	96.00%	60.00%	82.50%	73.00%	83.00%
		min	16,612	5,405	5,953	45,557	27,000	26,979	9,975	149,468	1,638	12,935	30
		max	23,439	8,438	8,672	76,958	38,016	40,468	11,640	418,509	2,457	17,041	144
Amount of VS	[tons/a]	average	20,026	6,894	7,313	61,257	32,364	33,723	10,808	283,988	2,048	14,988	87
		min	380	300	300	360	600	460	550	310	414	250	400
		max	400	420	417	686	623	490	669	486	613	620	650
Biogas potential	[m³/ton VS]	average	390	360	358	523	611	475	610	398	514	435	525
		min	60%	50%	50%	50%	50%	50%	51%	58%	58%	60%	50%
		max	65%	60%	60%	70%	70%	60%	65%	70%	70%	65%	60%
Methane content	[%]	average	63%	55%	55%	60%	60%	55%	58%	64%	64%	63%	55%
		min	228	150	150	180	300	230	281	180	240	150	200
		max	260	252	250	480	436	294	435	340	429	403	390
Methane potential	[m³/ton VS]	average	244	201	200	330	368	262	358	260	335	277	295
		min	34	30	93	13	68	32	37	27	36	24	8
		max	55	78	225	60	138	62	68	143	97	84	70
Methane potential	[m³/ton FM]	average	45	54	159	37	103	47	52	85	66	54	39
		min	3,787,539	810,689	892,891	8,200,216	8,100,000	6,205,101	2,797,988	26,874,257	393,120	1,940,203	6,065
		max	6,094,143	2,126,322	2,168,098	36,939,903	16,574,976	11,897,607	5,063,400	142,376,762	1,054,872	6,867,498	56,020
Methane yield	[m³]	average	4,940,841	1,468,506	1,530,495	22,570,059	12,337,488	9,051,354	3,930,694	84,625,509	723,996	4,403,850	31,042
		min	37,875,395	8,106,893	8,928,910	82,002,156	81,000,000	62,051,010	27,979,875	268,742,565	3,931,200	19,402,031	60,648
		max	60,941,429	21,263,222	21,680,984	369,399,030	165,749,760	118,976,067	50,634,000	1,423,767,618	10,548,720	68,674,978	560,196
Total energy	[kWh/a]	average	49,408,412	14,685,057	15,304,947	225,700,593	123,374,880	90,513,539	39,306,938	846,255,092	7,239,960	44,038,505	310,422
		min	14,392,650	3,080,619	3,392,986	31,160,819	30,780,000	23,579,384	10,632,353	102,122,175	1,493,856	7,372,772	23,046
		max	25,595,400	8,930,553	9,106,013	155,147,593	69,614,899	49,969,948	21,266,280	597,982,400	4,430,462	28,843,491	235,282
Electricity production	[kWh_{therm}/a]	average	19,994,025	6,005,586	6,249,499	93,154,206	50,197,450	36,774,666	15,949,316	350,052,287	2,962,159	18,108,131	129,164
		min	11,362,618	2,432,068	2,678,673	24,600,647	24,300,000	18,615,303	8,393,963	80,622,770	1,179,360	5,820,609	18,194
		max	21,938,914	7,654,760	7,805,154	132,983,651	59,669,914	42,831,384	18,228,240	512,556,342	3,797,539	24,722,992	201,671
Heat generation	[kWh_{el}/a]	average	16,650,766	5,043,414	5,241,914	78,792,149	41,984,957	30,723,344	13,311,101	296,589,556	2,488,450	15,271,801	109,932
		min	1.62	0.35	0.38	3.51	3.47	2.66	1.20	11.52	0.17	0.83	0.003
		max	2.74	0.96	0.98	16.62	7.46	5.35	2.28	64.07	0.47	3.09	0.025
Installed capacity	[MW_{el}]	average	2.18	0.65	0.68	10.07	5.47	4.01	1.74	37.79	0.32	1.96	0.014

Table 3-2. Data on biogas potentials from wastewaters (Fischer, Schmidt et al. 2010).

	Unit		Coffee processing wastewater	Dairy wastewater	Slaughterhouse wastewater	Distillery stillage	Nut processing wastewater	Pineapple processing wastewater	Sisal decortications wastewater
Amount of wastewater	[m³/a]		4,104,000	1,083,000	60,000	108,000	9,216	840,000	2,460,200
Ammount of COD in wastewater	[g/l]	min	1	2	5	55	4	3	8
		max	28	6	11	125	4	8	15
		average	14	4	8	90	4	6	12
Amount of COD	[tons/a]	min	2,462	2,166	300	5,940	37	2,520	19,682
		max	114,912	6,498	660	13,500	40	6,720	36,903
		average	58,687	4,332	480	9,720	38	4,620	28,292
COD degradability	[%]	min	85%	85%	55%	52%	65%	80%	80%
		max	95%	90%	98%	80%	75%	90%	93%
		average	90%	88%	77%	66%	70%	85%	87%
Biogas potential	[m³/ton $COD_{rem.}$]	min	350	333	320	330	308	300	427
		max	400	400	360	450	353	450	523
		average	375	367	340	390	330	375	475
Methane content	[%]	min	60%	75%	60%	60%	65%	65%	82%
		max	80%	85%	78%	85%	85%	85%	86%
		average	70%	80%	69%	73%	75%	75%	84%
Methane potential	[m³/ton $COD_{rem.}$]	min	210	250	192	198	200	195	350
		max	320	340	280	383	300	383	450
		average	265	295	236	290	250	289	400
Methane potential	[m³/ton FM]	min	0	0	1	6	1	0	2
		max	9	2	3	38	1	3	6
		average	4	1	2	22	1	2	4
Methane yield	[m³]	min	439,538	460,275	31,680	611,582	4,792	393,120	5,510,848
		max	34,933,248	1,988,388	181,156	4,131,000	8,999	2,313,360	15,443,906
		average	17,686,393	1,224,332	106,418	2,371,291	6,896	1,353,240	10,477,377
Total energy	[kWh/a]	min	4,395,384	4,602,750	316,800	6,115,824	47,923	3,931,200	55,108,480
		max	349,332,480	19,883,880	1,811,557	41,310,000	89,994	23,133,600	154,439,055
		average	176,863,932	12,243,315	1,064,179	23,712,912	68,959	13,532,400	104,773,768
Electricity production	[$kWh_{therm.}$/a]	min	1,670,246	1,749,045	120,384	2,324,013	18,211	1,493,856	20,941,222
		max	146,719,642	8,351,230	760,854	17,350,200	37,798	9,716,112	64,864,403
		average	74,194,944	5,050,137	440,619	9,837,107	28,004	5,604,984	42,902,813
Heat generation	[kWh_{el}/a]	min	1,318,615	1,380,825	95,040	1,834,747	14,377	1,179,360	16,532,544
		max	125,759,693	7,158,197	652,161	14,871,600	32,398	8,328,096	55,598,060
		average	63,539,154	4,269,511	373,600	8,353,174	23,387	4,753,728	36,065,302
Installed capacity	[MW_{el}]	min	0.19	0.20	0.01	0.26	0.002	0.17	2.36
		max	15.72	0.89	0.08	1.86	0.004	1.04	6.95
		average	7.95	0.55	0.05	1.06	0.003	0.60	4.66

3.2. Mully Children's Family (MCF) Yatta, Kenya - Site description

3.2.1. Identity of the MCF organization

MCF, according to their own definition, is a non-profit making, non-political, non-governmental Christian organization founded in 1989 by Dr. Ev. Charles Mulli and Esther Mulli (Anonymous 2012c). Their main work and mission is centered on providing care and rehabilitation to street or slum children and teenagers, orphans and underage mothers, among other. For this purpose, five MCF homes have been established in different regions in Kenya, with a population of over 2000 in the year 2012 (Anonymous 2012c). Shelter, food, education and training are offered in these homes. In order to ensure financial independency and sustainability, MCF's action has expanded to agricultural activities that to some extent have managed to supplement funding from external sources. In collaboration with Norwegian Church Aid (NCA) they have incorporated environmental conservation projects in their activities, in order to achieve sustainability and become a model for raising awareness on environmental issues like climate change (Anonymous 2012c).

3.2.2. Site activities and population

The study site is the MCF home at Yatta district (figure 3.1.), where environmental conservation activities have been integrated to the agricultural activity. These activities include agroforestry, general irrigation farming techniques, hydroponics, rainwater harvesting and modern farming technology. In order to adopt low carbon development paths, MCF is aspiring to include the use of renewable energy technologies, such as wind energy, solar power, biomass and biogas (Anonymous 2012c). The site's main divisions are the administration offices of the organization, the fields, the animal farms, and the main area which included other offices, classrooms, several training centers, kitchen, nursery, dispensary and the homes of the children. The total population that either resided or worked at the site was at the moment of visit 639 persons: 24 persons at the offices (including daily visitors), 120 day workers occupied at agricultural and other activities, 80 persons permanent staff

(teachers, social workers, kitchen staff etc.) at the main area, 350 students and 65 children under the age of 3. Out of the 639 persons approximately 430 were staying overnight at the farm facilities. Among them are the students, the children and some of the main staff. The anticipated future population growth will not be taken into consideration in this present thesis.

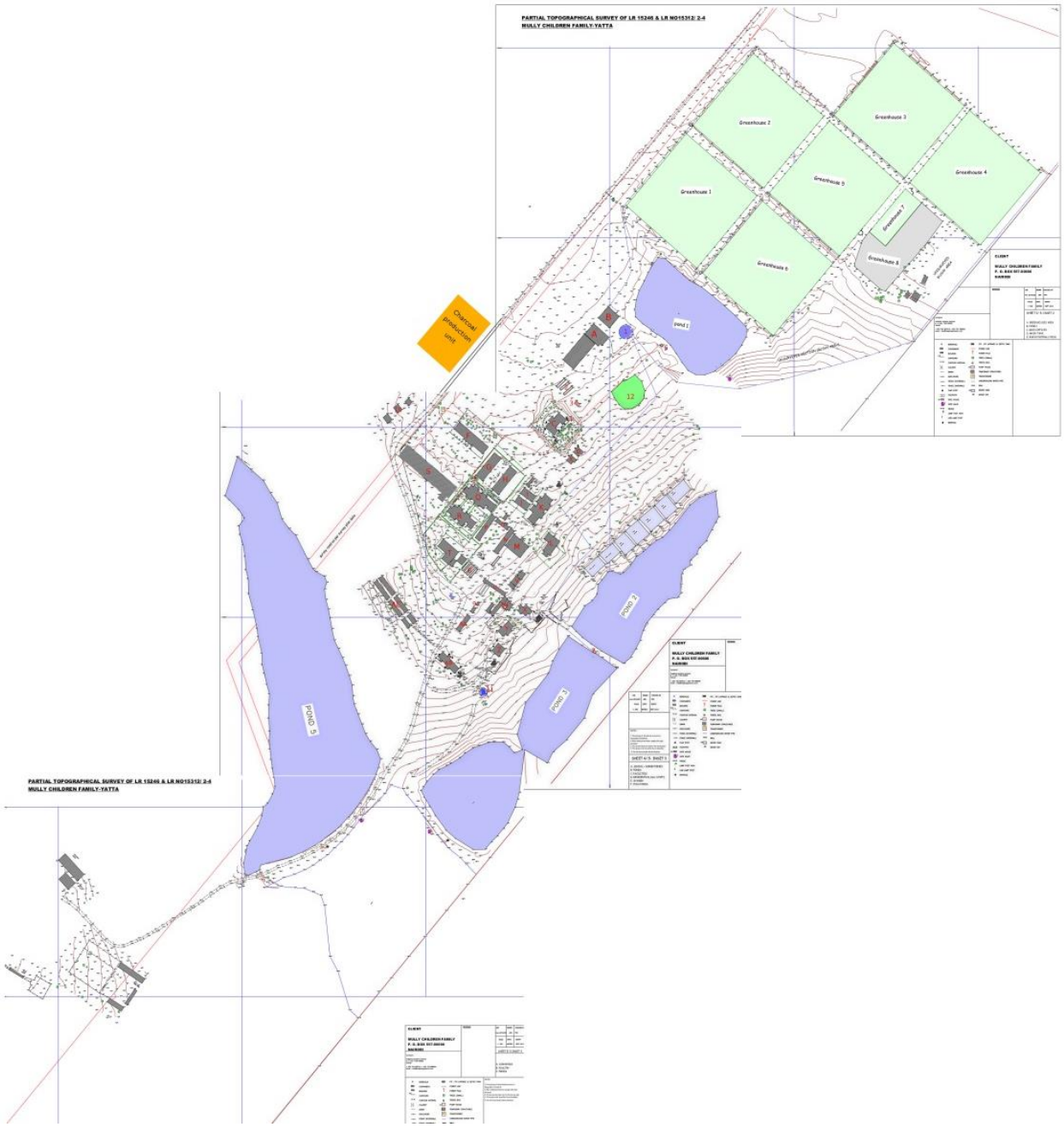

Figure 3.1. Map of MCF Yatta.

3.2.3. Natural conditions

MCF Yatta is located in Machakos County, 70km east from Nairobi along Thika-Garissa Highway. Machakos County has a semi-arid climate, with a hilly terrain covering most of its parts and an altitude ranging from 1000 up 1600 m above sea level (Machakosgoverment.com 2013). There are two main rain seasons during the year, one between March and May and a smaller one between October and December. The mean annual precipitation for the years 2007 to 2011 was 863.1 mm and the mean temperature 20.15^{o}C. The monthly precipitation can be seen in the graph and the daily minimum and maximum temperature per month in the table. The climatic data (figure 3.2 and table 3.3) from Thika meteorogical station nearby Yatta farm were obtained by MCF from the Kenyan Meteorological Department (2012). Geological maps of the area had to be requested from the Mines and Geology department of the Kenyan Ministry of Environment, Water and Natural Resources, but this was not feasible at the time. The people from MCF explained that the Ministry is not very flexible when it comes to providing mining/geological maps. Hydrogeological maps were also not available.

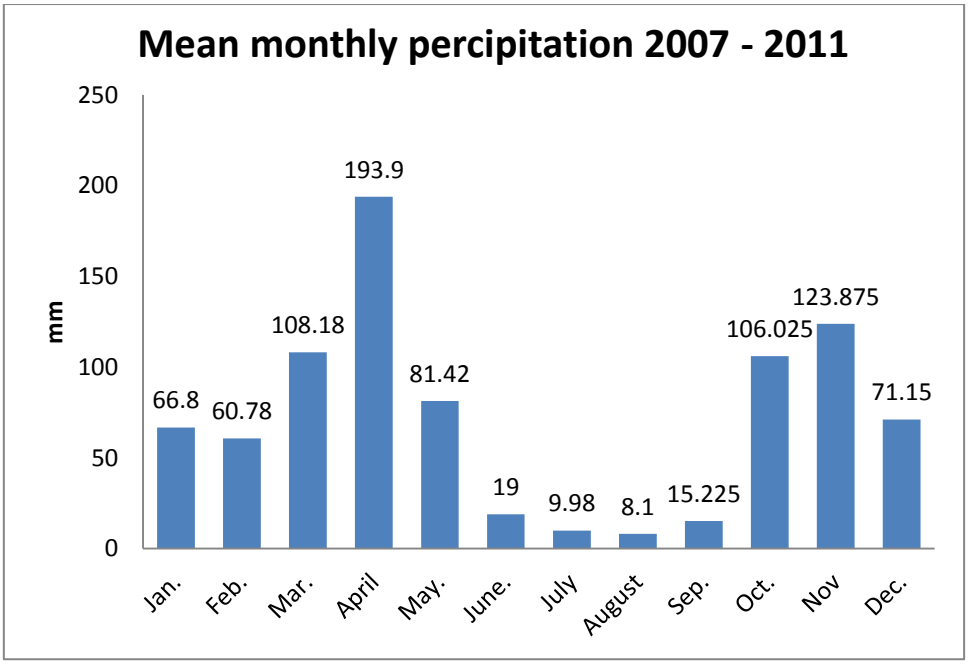

Figure 3.2. Mean monthly precipitation 2007 – 2011 (Kenyan Meteorological Department 2012).

Table 3-3. Daily minimum and maximum temperature per month 2007 – 2011 (Kenyan Meteorological Department 2012).

Temp. °C	Year	Jan.	Feb.	Mar.	April	May.	June	July	Aug.	Sep.	Oct.	Nov	Dec.
Daily max.	2007	25.6	28.3	27.8	26.3	25.5	25	23	23.3	26.3	26.8	22	22.9
Daily min.	2007	15	14	14.8	16.1	16	14.1	13.5	13.9	13.4	13.3	14.2	13.5
Daily max.	2008	26.9	27.3	28.2	25.8	25.3	23.7	23.1				22.9	23.7
Daily min.	2008	13.6	13.3	15.8	15.8	15	13.5	13.3			14	14.7	14.6
Daily max.	2009	28.6	29.2	30.4	28.2	26.6	28	25.4	25.2	28.6	26.9	23.4	24.3
Daily min.	2009	12.9	13.9	14.7	16.5	15.8	14	11.5	12.9	14.1	14	14.5	13.6
Daily max.	2010	26.4	27.3	26.6	26.7	25.5	24	23.3	23.5	26.7	28	24.8	26.5
Daily min.	2010	14.2	16.4	15.5	17	16.1	14.3	12.7	12.8	12.9	15.3	15.6	13.9
Daily max.	2011	27.9	29.2	28.6	26.9	26	25.3	25.7	23.8	26.5	26.5		26
Daily min.	2011	12.3	12	14.7	16.7	16	14.3	11.7	13.5	14.2	15.7		14.9

3.3. Methodology

The methods of data collection were on-site inspections, interviews with the staff and workers and document reviewing. Each day, staff members and a guide were assigned to guide the mapping team through the sites of interest of the farm and to facilitate communication with the workers. All the appropriate documents were provided by the farm management. The main limitation of the methodology is that many of the numbers are estimations made by the responsible people at MCF Yatta based on their experience. Additionally, the amounts of waste represent fresh matter.

During the trip to Kenya, several meetings were made with the NCA branch in Kenya, since the project was supported by them. The meetings were very much needed in order to understand the nature of MCF organization and the background of the project, as well as the way that the project should be approached.

A meeting was also made with the African Center for Technology Studies (ACTS), which is an organization involved in many renewable energy projects, including biogas, in villages all over Kenya and neighboring countries and the policy making on

the matter. Their experience with relevant projects was discussed, as well as the policy and the trends regarding renewable energy production in Kenya and its use by everyday people.

Finally, an excursion to a local farm near the city of Matuu that used biogas technology took place. The farmer was operating a fixed dome bioreactor, designed by GIZ. The bioreactor was fed with 200kg of dairy slaughter house waste and 200kg vegetable waste twice per day. The feedstock was grinded and mixed with water before being fed to the bioreactor. The produced biogas was mainly utilized in a modified diesel generator that was providing electricity to the water pump and to a smaller extent in cooking and lighting. The slurry was left to dry for an appropriate time and then was used as fertilizer, while the effluent was used to irrigate flowers. Minor problems included gas leaking and occasionally low gas pressure. The farmer was overall satisfied with the performance of the bioreactor.

a) b) c)

d) e) f)

Figure 3.3. Biogas at Matuu farm a) fixed dome compartment, b) slurry drying bed, c) mechanical grinder and mixing pit / inlet, d) gas inlet of the modified generator, e) biogas lamp and f) biogas cook stove. *Photos: I. Georgiadis (2013).*

3.4. Data collection

The agricultural activities that take place at the MCF farm at Yatta offer a wide range of appropriate substrates for biogas production. Theses substrates include agricultural waste leftovers, vegetable waste, animal manure (figure 3.4) and to a small extent slaughter waste. Additionally, human fecal sludge that is collected on-site in pit latrines and kitchen organic refuse are also eligible to be used as feedstock for biogas production.

3.4.1. Animal waste

The acquired data for the waste produced from the farm animals per year can be seen in the following table 3.4. The waste is divided into two categories: animal manure and slaughter waste.

Figure 3.4. Animal husbandry at MCF Yatta. *Photo: I. Georgiadis (2013)*

Cow dung consists the largest fraction of the animal manure. At MCF there are 91 free grazing cows, of which 59 were adult and 32 young ones. The goats were 53 adult and 9 young ones. The sheep were 108 adult and 4 young ones. Animal manure was left to dry for a long time period, usually months, and then was used for compost production and fertilizer (figure 3.5). A large amount of manure was lost due to free grazing.

a) b)

Figure 3.5. a) Drying manure, b) scattered cow dung due to free grazing. *Photos: I. Georgiadis (2013)*

Poultry litter and droppings were also collected and left to dry for long time periods, before being used as fertilizer (figure 3.6).

a) b)

Figure 3.6. a) Poultry farming at MCF Yatta, b) dry composting of poultry litter. *Photos: I. Georgiadis (2013)*

Slaughter waste is mainly produced from the small scale commercial activity of the farm involving poultry production. Slaughtering was conducted on-site and there was no method of collecting the waste, including the blood and feathers. Moreover, some poultry body parts, like feet and heads, were sold to tribes that are accustomed to use

them in their traditional cuisine. Fish were sold unprocessed, so slaughter waste was produced only by the fish that were consumed in the farm. For this reason this waste can be included to the kitchen organic refuse that will be presented in a later paragraph.

Table 3-4. Waste from farm animals per year at MCF Yatta.

Type of animal breed	Total number	Cycles	Total amount of waste (tons)	Waste types
Cows	91	annual	64	Cow dung
Sheep	112	annual	15.5	Droppings
Goats	62	annual	9.3	Droppings
Poultry production	818	8 cycles	8.2	Litter and droppings
Poultry slaughter waste	818	8 cycles	1.63	Feathers and off cuts
Fish (Tilapia)	24000	8 months	0.2	Slaughter waste

3.4.2. Vegetable waste

There is high agricultural activity at MCF, which produces a considerable amount of agricultural residues that can be used for biogas production (table 3.5.).

Table 3-5. Vegetable waste at MCF Yatta.

Type of crops	Type of residue	Area ha/year	Amount of waste	Rotations and cycles per year
French beans	Plant waste	15 ha	120 tone	52
Maize	Maize Stover	10 ha	60 tone	3
Organic waste from other crops	Un-consumable part of vegetables	10 ha	10 tone	N.S.*

N.S.*: not specified

French beans are covering 15 ha and are the main crop type. Around the year, 0.5 ha per week are being planted. The estimated waste is 5-6 tons per 0.5 ha. Maize crops (figure 3.7) cover 10 ha. There are two maize crops, that are being harvested every March and August, plus a rotational one. Residue waste from both crop types for the moment is being fed to the livestock.

Figure 3.7. Maize crops at MCF Yatta. *Photo: I. Georgiadis (2013)*

The organic waste from other crops include un-consumable parts, residues and rotten vegetables among other and were collected in barrels and used as animal feed or for compost production (figure 3.8). This amount of waste leftovers from the commercial activities of the farm varies, depending on how much the production is. This fraction can be included to the kitchen refuse that will be presented later.

Figure 3.8. Collection of vegetable residue waste in barrels at MCF Yatta. *Photo: I. Georgiadis (2013)*

3.4.3. Human waste

Waste from human activities is separated in two categories. First, human fecal sludge and second organic waste and food leftovers produced in the kitchen that serves the students and the staff.

The fecal sludge collected in the pit latrines will be in focus, since no flush water is used. This means that the volume of the wastewater is less and more concentrated. There are in total 50 pit latrines at MCF Yatta; 24 close to the school area, 14 close to the lower houses, 8 close to the farm offices and 4 scattered in various locations. The persons using the 38 pit latrines, located in the main farm area and the school, are the students and children of the farm, as well as the teachers and the staff. The number of these persons is approximately 430 and the amount of fecal sludge produced by them will be considered in the calculations. The rest 12 pit latrines that were located in scattered spots around the farm and were predominantly used by the daily workers in the fields were not included, because there is great variability in their number and no safe estimation of the produced amount of fecal sludge can be made.

Figure 3.9. Pit latrines at MCF Yatta. *Photo: I. Georgiadis (2013)*

Literature sources sate that the average excreta production per person per year is 550l (Jennsen, Greatorex et al. 2004), so assuming this and that the number of persons is 430, the total amount of fecal sludge is estimated to be 236500l per year.

The kitchen serves 3 meals per day to more than 400 persons (including students, teachers and personnel). The composition of the waste can be considered steady, since the daily menu is not a subject of great variation. There was no collection method of the kitchen waste (figure 3.10) and so they were discarded to a compost pit, among inorganic waste that was being burned. In order to estimate the volume, the kitchen waste was collected for three days (figure 3.11). The net weight of the waste was 0.124 tons after three days, so 0.0413 tons/day which equals to 15.08 tons of fresh matter per year**.** The 10 tons of agricultural residues (from table 3.5) from the farms yearly commercial activity are of the same nature, so they can be added, as well as the 0.2 tons of fish slaughter waste (from table 3.4) that were consumed on-site. This makes the total amount of kitchen waste to be 25.28 tons of fresh matter per year.

Figure 3.10. Organic waste produced in the kitchen. *Photo: I. Georgiadis (2013)*

a) b)

Figure 3.11. . a) Kitchen waste 1st day of collection b) Kitchen waste 3rd and final day of collection. *Photos: I. Georgiadis (2013).*

Chapter 4 : MCF Yatta - Estimation of the methane potential and system proposal

4.1. Methane potential estimation

An accurate estimation of the methane potential of the waste produced at MCF Yatta is difficult to be made. In order to estimate the biogas and methane yields of the different biodegradable waste fractions empirical data is used.

In the following table 4.1, methane or biogas yields of different substrates extracted from selected literature sources are presented. Gas production for the same substrate is being expressed in different ways, so in some cases, chemical parameters, such as VS and COD are necessary for the calculations. Such calculations were not possible to be made at MCF. The fact that the amounts of waste produced on the study site represent fresh matter and the many different ways that these references are expressed elucidates the difficulty that arises in estimating the methane potential of at MCF.

Table 4-1. Methane or biogas yields from selected literature sources.

Type of waste		Yield	Unit	Reference
Animal waste	***Cow dung***	0.023-0.04	m^3 biogas/ kg F.M.*	(Lam and Heegde 2007)
		0.027	m^3 CH_4/ kg F.M.*	(Al Seadi 2008)
		0.233	m^3 CH_4/ kg VS added	(Lehtomäki 2006)
		0.166	m^3 CH_4/ kg VS added	(Amon, Amon et al. 2007) (dairy cattle manure)
		0.056-0.2	m^3 CH_4/ kg VS added	(ISAT and GTZ)
	Sheep/goats	0.09-0.31	m3 biogas/ kg VS added	(ISAT and GTZ)
	Poultry manure	0.065-0.116	m^3 biogas/ kg F.M.*	(Lam and Heegde 2007)
		0.048	m^3 CH_4/ kg F.M.*	(Al Seadi 2008)
		0.054	m^3 CH_4/ kg F.M.*	(Fischer, Schmidt et al. 2010)
		0.2-0.37	m^3 CH_4/ kg VS added	(ISAT and GTZ)
	Poultry slaughter waste	0.7-0.9	m^3 CH_4/ kg VS added	(Salminen and Rintala 2002) (Offal, feet and head)
		0.6-0.7	m^3 CH_4/ kg VS added	(Salminen and Rintala 2002) (trimmings and bone)
Agricultural waste	***French beans***	0.343	m^3 CH_4/ kg VS added	(Nallathambi Gunaseelan 1997)
	Maize	0.291-0.338	m^3 CH_4/ kg VS added	(Weiland 2010) (Energy crop yield)
		0.312-0.365	m^3 CH_4/ kg VS added	(Amon, Amon et al. 2007) (Energy crop yield)
		5780	m^3 CH_4 / ha / year	(Weiland 2003) (Energy crop yield)
Human waste	***Fecal sludge***	0.03-0.05	m^3 biogas/ kg F.M.*	(Lam and Heegde 2007)
		0.01	m^3 CH_4/ person / day	(Wendland, Deegener et al. 2006) (black water from vacuum toilets)
		0.535-0.672	m^3 CH_4/ kg VS added	(Lim 2011) (brown water)
		0.137	m^3 CH_4/ kg COD added	(Gallagher 2010)
	Kitchen refuse	0.039	m^3 CH_4/ kg F.M.*	(Fischer, Schmidt et al. 2010) (Vegetable waste)
		0.5-0.6	m^3 biogas/ kg VS added	(Al Seadi 2008) (Food remains)
		0.37-0.394	m^3 CH_4/ kg VS added	(Viturtia, Mata-Alvarez et al. 1989) (Fruit and vegetable waste mixture)
		0.173-0.288	m^3 CH_4/ kg VS added	(Lim 2011) (Food waste)

F.M.*: Fresh matter

4.1.1. Estimated methane and biogas potential at MCF Yatta

Based on the above table 4.1, a theoretical methane potential estimation of selected resources at MCF Yatta is presented in the following table 4.2 and represented graphically in figure 4.1. The residue waste from the French bean and maize crops weren't included because their current use as animal feed is considered quite beneficial.

Table 4-2. Methane potential estimation of selected resources at MCF Yatta.

Type of waste	Total Amount	Unit	CH_4 yield	Unit	Total CH_4 estimated potential	Unit	Reference
Cow dung	64000	kg/year	0.027	m^3 CH_4/ kg F.M.*	1728	m^3/year	(Al Seadi 2008)
Poultry manure	8200	kg/year	0.054	m^3 CH_4/ kg F.M.*	442.8	m^3/year	(Fischer, Schmidt et al. 2010)
Fecal sludge	430	persons	0.01	m^3 CH_4/ person / day	1569.5	m^3/year	(Wendland, Deegener et al. 2006) (collected from vacuum toilets)
Kitchen refuse	25280	kg/year	0.039	m^3 CH_4/ kg F.M.*	985.92	m^3/year	(Fischer, Schmidt et al. 2010) (vegetable waste)
Total					4726.22	m^3/year	

F.M.*: Fresh matter

There is a total estimated potential of 4726.22 m^3 CH_4/year or 12.95 m^3 CH_4/day is at MCF Yatta. Assuming that methane content in the produced biogas will be 60%, then the total estimated amount of biogas is 7877 m^3/year or 21.58 m^3/day. The total actual potential can be considered to be higher for various reasons. First not all the resources are included. Second, the amount of resources represents the present situation at MCF and the future plans for expansion are not considered.

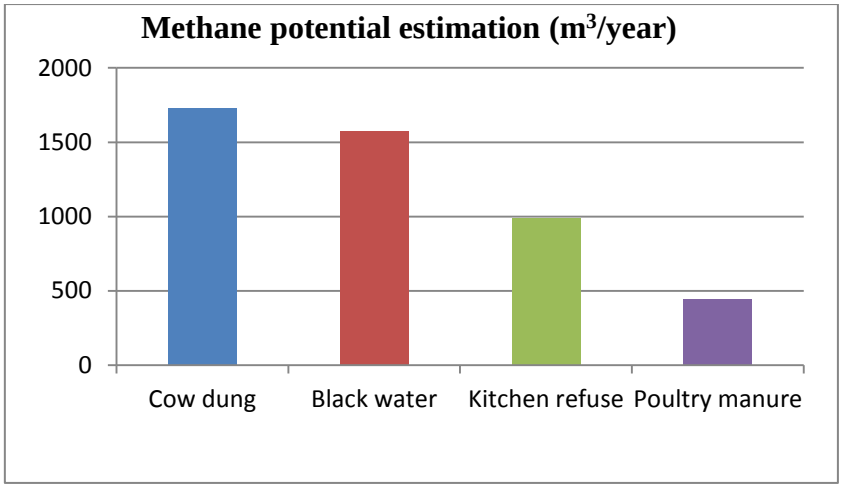

Figure 4.1. Methane potential estimation of selected resources at MCF Yatta.

The methane produced by the different selected substrates can be converted to energy equivalent and selected fuels tonnage equivalents (table 4.3). The numbers have been based on ration taken from the work of Ngumah, Ogbulie et al. (2013) (Ngumah, Ogbulie et al. 2013). The energy equivalent of the estimated methane potential is 184.3 GJ. The numbers in the table may be overestimating the actual energy equivalent of the produced methane.

Table 4-3. Energy equivalent and fuels tonnage equivalents.

Type of waste	CH_4 estimated potential m^3/year	Energy equivalent GJ/year	Wood fuel equivalent (tons/year)	Coal equivalent (tons/year)	Kerosene equivalent (tons/year)	Liquefied petroleum gas equivalent (tons/year)
Cow dung	1728	67.4	4.58	2.68	1.56	1.45
Black water	1569.5	61.2	4.1624	2.4381	1.419	1.3201
Kitchen refuse	985.92	38.5	2.61	1.53	0.89	0.83
Poultry manure	442.8	17.3	1.17	0.69	0.40	0.37
Total	4726.22	184.3	12.53	7.34	4.27	3.98

4.3. System proposal

The following system is proposed (figure 4.2). The technology recommended for MCF Yatta is the fixed dome reactor. The bioreactor can be fed continuously with fecal sludge from pit latrines and kitchen refuse and vegetable waste, which is

produced daily in approximately same amounts and composition. The feeding of the bioreactor with animal manure and agricultural waste is recommended for increasing the biogas yield. Moreover, animal manure is required for seeding the population of the methanogens in the substrate. The produced biogas can be utilized in cooking and lighting. The size of the digester and the detailed technical aspects of the system exceed the objectives of this present thesis.

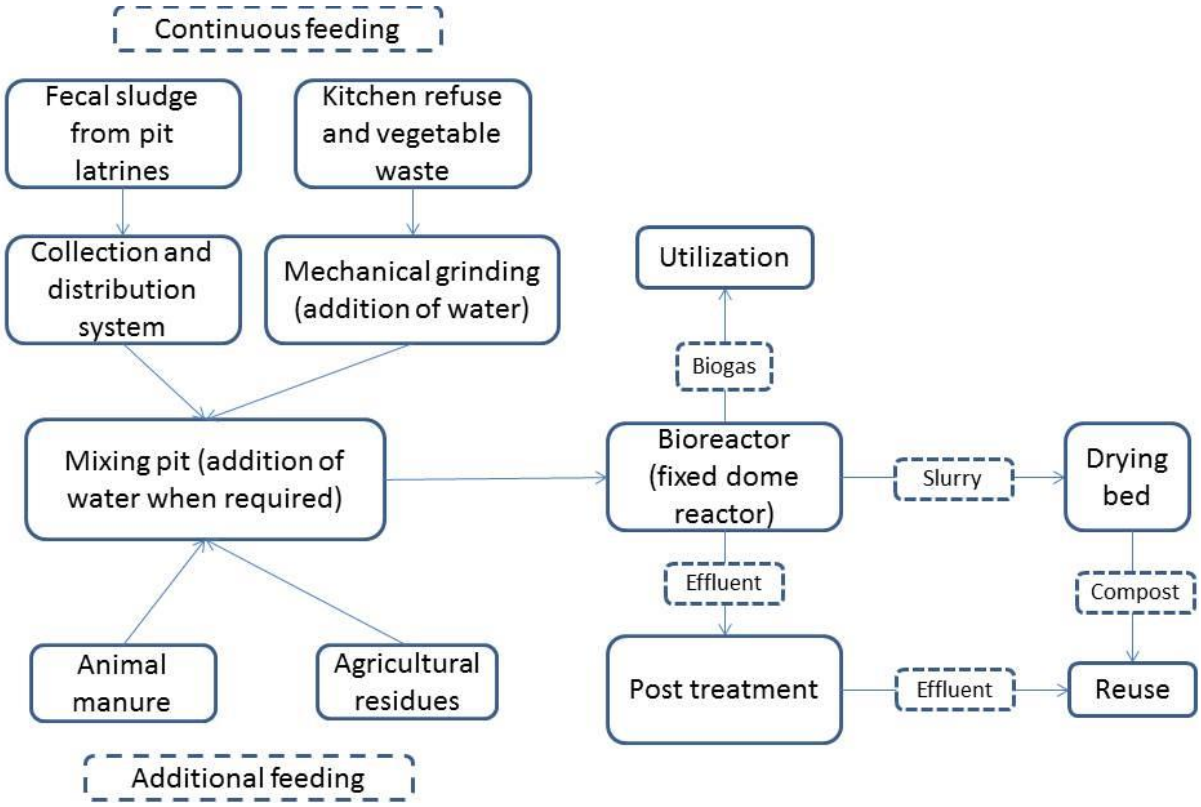

Figure 4.2. Proposed system for MCF Yatta.

4.4. Discussion

4.4.1. Realization of the system

The collection of the toilet waste or fecal sludge is currently being done in pit latrines. There are three options of feeding the bioreactor with the fecal sludge. The first option is regular pumping of the latrines using a vacuum truck. This is the way the latrines are being emptied at the moment. However, harmful pollutants can infiltrate in the groundwater table from the open bottom of the latrines and also nutrients are

lost, especially nitrogen. The second option is direct feeding into the digester through pipes, though it might be difficult using undiluted excreta. This will depend on the location of the of the pit latrines in relation with the digester. By installing a low flush toilet system a piping system would be facilitated. The third option is collecting the fecal sludge in smaller barrels or containers under each latrine hole. This option is cheaper than a piping system since there is no need of excavation and installation, but special care needs to be taken by the people handling the barrels and emptying them into the system in order not to pose additional risks to the public or themselves.

Vegetable waste degrades rapidly and should thus be processed immediately, so as to avoid flies, rodents and odors. However, due to the seasonal character of the production some temporary storage may be necessary.

The kitchen refuse and vegetable waste have to be homogenized and diluted before it is fed into the digester. For this reason a mechanical grinder is necessary. After grinding, the homogenized material can enter the mixing pit and be further diluted with water if necessary and mixed with the fecal sludge.

4.4.2. Bioreactor

The fixed dome plant is widely used in Kenya and there are specially trained and experienced masons accessible for the construction. Moreover, there is the local successful use of the technology at the farm at Matuu that can serve as an example. A significant benefit from the construction of the fixed dome reactor will be the creation of job opportunities for the local community and the students. The students can also benefit by training in constructing, operating and maintaining the fixed dome plant.

The type of the reactor has been described in the theory part. A big drawback in the proposed system, regarding providing biogas energy for cooking and lighting is that the fixed dome plants sometimes fail to provide the constant gas pressure that is needed for both of these features.

4.4.3. Biogas utilization

Cooking

The energy demand in cooking is directly related with the eating habits of the people using the stove. Traditional Kenyan food includes Ugali, which is a thick porridge made by maize meal, and Khitcherie (figure 4.3), which is made mainly with beans. Both require a long period of cooking with strong heat, from one to four hours. Rice is served for lunch and dinner almost every day. Additionally, tea consumption, which requires water boiling, is very high.

Figure 4.3. Khitcherie. *Photo: I. Georgiadis (2013).*

The fuel used for cooking in the kitchen at MCF Yatta is the traditional firewood. A total amount of 120 tons/year is consumed according to their estimations. Using firewood is not effective, since there is big energy loss and moreover the fumes produced with burning are highly harmful (figure 4.4).

Figure 4.4. Cooking with traditional firewood stoves at MCF Yatta. *Photos I. Georgiadis* (2013).

There's definitely the need of upgrading the cook stoves that are in use at the moment. Biogas cook stoves could be a clean alternative. According to Sasse (1998) energy produced by 1 ton of wood fuel (used for cooking) is equivalent to 180m^3 biogas. Using this ratio, the total estimated biogas potential of 7877 m^3/year is equivalent to 43.76 tons of wood fuel per year. However it has to be noted that using biogas cook stoves is more efficient than using traditional cook stoves. Biogas cook stoves have been reported to have efficiency 55%, while traditional cook stoves using wood, charcoal or dung have an efficiency that ranges from 10.2 to 19% (Bhattacharya and Abdul Salam 2002). More recent findings suggest that the efficiency of biogas cook stoves can reach up to about 60.01%, while the hourly biogas consumption is 0.375m^3 (Kurchania, Panwar et al. 2011). Adopting an efficient cook stove with hourly biogas consumption like the last referred one will mean that the estimated 21.58 m^3 biogas/day will be equal to 2.4 operating hours per day. A relatively big biogas stove with a 6'' burner consumes 0.57 m^3 biogas/hour according to FAO (1996). This, for the potential of MCF Yatta, translates to 1.58 operating hours per day.

The total amount of biogas produced cannot cover the full energy needs for cooking. However, significant savings can be made.

Lighting

The biogas produced can be utilized in lighting by using biogas lamps, replacing the kerosene lamps that are used at MCF and are the norm in rural areas in Kenya. It has been measured that kerosene lamps compared to other lamp types, like LED lamps exhibit the highest costs per unit of light output (Mills 2003). It has been reported that a 60W equivalent light bulb averagely consumes 0.135m^3 biogas/hour (Sasse 1998). Using this empirical number the total estimated 21.58 m3 biogas/day could translate to 6.7 operating hours per day.

4.4.4. Slurry and effluent treatment and reuse

The slurry that is coming in the outlet of the fixed dome plant should not be used directly. Safe handling and application on the field is of great importance for health

and environmental safety reasons. It can be collected in drying beds, which in fact are shallow compost pits and can be constructed parts of the main biogas plant. The following measures are recommended: a) construction of keep surface runoff water to enter the drying bed, b) at least two pits should be used, of which one will be used at the time and the others for additional volumes, or resting periods in order to allow the collection of slurry produced within a month, thus reduced infiltration and evaporation rates, c) protection from flooding during the rainy seasons and d) a slope should be used, if possible, in order to avoid the use of pumps (ESF and seecon n.d.).

The effluent can be used directly for irrigating flowers or forest trees. However, since the hydrogeology of the site is not known, post treatment might be needed. A polishing bed with reeds is proposed.

4.4.5. Additional benefits

There are some additional indirect benefits of the system that are equally important. Even though the sanitation facilities of the site are in very good condition and comply with national and international regulations (figure 4.5), there is no on-site treatment method. The fecal sludge from the pit latrines is being collected periodically and is transported to the nearest conventional wastewater treatment plant. This adds to the expenses of the organization. Also, during the rain seasons some of the pit latrines may be subjected to flooding. Moreover, there is no handling and treatment plan for the kitchen waste. The bioreactor can contribute to the improvement of the on-site waste and wastewater management. By using clean biogas stoves, the indoor pollution from the burning of the firewood will be eradicated, thus the health condition of the kitchen staff will no longer be endangered from the harmful fumes.

a) b)

Figure 4.5. a) Lighting and b) hand washing facilities at the pit latrines at MCF Yatta. *Photos: I. Georgiadis (2013).*

Finally, MCF has the potential to serve as a model. Farmers from the local community follow the example. The successful implementation operation of the system could influence governmental and institutional policy makers in favor of biogas technology.

4.4.6. Limitations

The acidity related with using kitchen and vegetable waste as feedstock and the presence of ammonia in animal manure can pose as limiting factors.

Free grazing results to significant loss of the amount of cow manure, which has the highest theoretical potential. Switching to zero grazing would be beneficial for the proposed system. It has been reported that 38% more cow manure can be collected from zero grazing animals and 36.4% higher biogas yield and an additional amount of 4kg of biogas slurry per cattle can be produced (Worku 2010).

The limitations connected with biogas production in Africa have been summed up by Parawira, W. (2009) and those that can apply in the case of MCF Yatta are: a) assigning the construction to inexperienced contractors and consultants that can potentially result to a faulty construction with the wrong materials, b) inappropriate operation, maintenance and repair by inexperienced personnel without special training and technical knowledge and c) no support from the government with the right energy policy or academic institutes with the right research (Parawira 2009).

Chapter 5 : Biogas laboratory experiment - Materials and Methods.

5.1. Introduction

For the purpose of this thesis, a set of laboratory experiments for the determination of the methane potential of different substrates were conducted.

5.2. Materials and methods

5.2.1. Samples

Sampling took place at IMT labs at the Norwegian University of Life Sciences (UMB) the 13th of May 2013. Samples include black water, kitchen waste and a mixture of both. Approximately 5 liters of each fraction were taken in plastic cans. The sampling of the inoculum took place on the 27th of May 2013.

The black water (**BW**) sample is domestic wastewater that contains only excreta and small amount of flush water. The samples origin is the student dormitories at Kajaveien in Ås, Norway and were collected from low flush vacuum toilets.

The kitchen waste (**KW**) sample contains kitchen refuse and the organic fraction of the household waste, collected separately. The sample used were pursued by the IMT department from Norsk Matretur AS, and contained mainly kitchen waste from restaurants, among other, and were homogenized and pasteurized.

The black water and kitchen waste (**BW+KW**) sample is the mixture of both samples in 1:1 v/v proportion, though the dry matter of the KW was considerable higher. The mixture was used as feedstock for the anaerobic digester at IMT labs at UMB.

The inoculum (**IN**) was digested BW+KW feedstock that contained active methanogens and was collected from the anaerobic digester at IMT. The type of the digester was a continuous semi stirred reactor (CSTR) operating semi-continuously at mesophilic temperature. The digester was initially inoculated with sewage sludge from waste water treatment plant and animal manure. At the moment of IN sampling, the reactor had been digesting the sample for approximately 88 days.

5.2.2. Laboratory equipment

The laboratory experiment took place in the IPM labs and the IKBM labs form the end of May 2013 until the middle of July 2013. The following equipment was used:

- Four 10 l plastic cans for the collection of the samples.
- Four 5 l plastic cans for mixing the samples with the inoculum.
- Porcelain cups
- Oven to dry the samples at 105^{o}C for the calculation of the dry mater / total solids (TS).
- Oven to ash the samples at 550^{o}C for the calculation of the volatile solids (VS).
- One scale for measuring the weight.
- Twelve 500 ml glass bottles with air tight caps.
- One pH meter.
- An incubator at 35^{o}C that also provided shaking at 70 rpm.
- One 50 ml syringe for the measurement of the gas volume
- One electronic pressure gauge for measuring gas pressure in mbar.
- One gas chromatograph for measuring gas composition.

5.2.3. Experimental design and process

The experiment for the methane potential estimation of the BW, BW+KW and KW samples was carried out in 500 ml glass bottles. Three parallels for each sample were used, labeled BW I, BW II and BW III, BW+KW I, BW+KW II and BW+KW III and

KW I, KW II and KW III. Total working volume was 350 ml. The bottles were filled with 315 ml of substrate (90% v/v) and 35 ml inoculum (10% v/v). Also, three parallels of pure inoculum were set up, labeled IN I, IN II and IN III, in order to function as control and the correction of the amount of biogas produced from the substrates under study. A total of twelve bottle bioreactors were prepared.

The bioreactors were sealed with rubber septa and aluminum screw caps with opening to achieve anaerobic conditions. Subsequently they were put in the incubator for incubation at 35^{o}C and shaking at 70 rpm. Gas pressure was measured with electronic pressure gauge and gas volume with a 50 ml glass syringe. Gas composition determination was made possible using a gas chromatograph.

The pH of the samples was mistakenly adjusted after the inoculation of the samples. Also, initial loading of the KW was too high. For these reasons, on day 9, a second set of BW+KW and KW samples were prepared. In both cases, the IN was provided by the IN III bottle to ensure that there will be an active methanogenic bacteria colony included.

The second set of BW+KW samples was labeled BW+KW I', BW+KW II' and BW+KW III'. This time the pH was adjusted before mixing with IN. No dilution was made in the new set of these samples, so there was the same feed to inoculum ratio and the same amount of TS and VS gr/l. Moreover, BW+KW bottle I from the first set of samples was followed for comparative reasons until day 23, when gas production eventually stopped.

The new set of KW samples had to be prepared, labeled KW I', KW II' and KW III'. Dilution was made with tap water. The desired effect of dilution was to achieve TS content in the bottles approximately 50 gr/l (table A.5 in appendix A). The new samples were 26.3% KW sample, 10% IN and 63.7% tap water. Furthermore, this time pH was adjusted first before mixing with IN and bottling.

The pH of the second set of KW samples was occasionally measured and adjusted. Drastic raise of pH of the KW I' (table B.4 at appendix B), caused by excessive addition of 5M NaOH, damaged the AD process of the sample and therefore was

aborted since there was no sign that gas production will recover. On day 13 bottles KW II' and KW III' were opened and checked for pH and on the next day they were seeded with 20 ml of IN to rejuvenate gas production.

5.3. Laboratory analyses

5.3.1. TS and VS determination

Total solids (TS) and volatile solids (VS) were determined using standard methods (APHA. 1976).

TS:

First an amount of fresh sample is put in a porcelain cup and weighed on a tarred weighing scale. Afterwards the samples were left to dry for a week at 105±5 C°. The dried samples are then weighed again. The dry matter is calculated using the following equation 1:

$$TS\% = \frac{\text{Dried sample weight}}{\text{Sample weight}} * 100$$

VS

The dried samples were placed in smaller porcelain cup. The same procedure was followed. The porcelain cups were first weighed empty and then with the dried samples. Afterwards they were put in the oven at 550°C and then weighed again. The volatile solids were calculated using the following equation 2:

$$VS\% = \frac{\text{Cup and dried sample weight - cup with incinerated sample weight}}{\text{Dried sample weight}} * 100$$

5.3.2. Preparation and incubation of samples

After TS and VS determination, on the 31st of May 2013, the samples were mixed with the active inoculum. The desired ratio (90% sample, 10% inoculum) was achieved in a total mixture of 2000 ml for each of the three samples (1800 ml sample, 200 ml inoculum) and stored in plastic cans. Due to the nature of the samples, especially the KW, intense mixing of the plastic cans was required in order to achieve homogenization.

The 500 ml bottles were filled with 350 ml mixture using a funnel. From the total volume of 2000 ml, 950 ml mixture was spared and stored for further analyses. The twelve bottles were then sealed and refrigerated at 3.8 ^{O}C, in order to postpone the process initiation. The reason was that access to the incubator would be possible after three days.

On the 3rd of June 2013 the bottles were put in the incubator (figure 5.1).

Figure 5.1. Incubator. *Photo: I. Georgiadis (2013).*

5.3.3. pH measurement and adjustment

The pH of the pure samples was measured using an electronic pH meter. Adjustment of the pH was made with the addition of either 1M or 5M NaOH.

5.3.4. Gas pressure and volume measurement

Gas pressure (mbar) was measured daily with an electronic pressure gauge (figure 5.2).

Figure 5.2. Gas pressure measurement with electronic pressure gauge. *Photo: I. Georgiadis (2013).*

Subsequently, gas volume (ml) was measured using a glass 50 ml syringe (figure 5.3). The advantage of the method used for the gas volume measurement was that it was quick and simple. The disadvantage was that the method was lacking accuracy, since some gas was escaping, and the glass syringe could collect only up to 50 ml gas and in many cases the total gas produced from one sample was more, so the glass syringe had to be filled with gas and emptied multiple times.

Figure 5.3. Gas volume measurement with 50 ml glass syringe. *Photo: I. Georgiadis (2013).*

Several other methods for gas collection and measurement are possible. Two of them were tried (figure 5.4). One was gas collection in a gas tight plastic bag and the other using displaced water with a syphon. Both methods are described by Stafford, Hawkes et. al. (1981). These methods were aborted because the available equipment was not enough for measuring all the bottles.

Figure 5.4. Alternate methods of gas measurement. *Photos: I. Georgiadis (2013).*

5.3.5. Gas composition

Gas composition was measured with a gas chromatograph (Perkin Elmer Autosystem). A small volume (0.5 ml) of gas was collected from each sample and then injected in the gas chromatograph. For the detection of the different gas components a thermal conductivity detector (TCD) was used with helium as a carrier gas. Temperature in the injection port and the column was 200°C, 65^{o}C in the column and the detection temperature was 250°C. For a percentage calculation of the gas concentration a standard gas was used (composition in mol%), methane (60,6%), CO2 (34.5%) and nitrogen (remaining), because the results were given in percentage area that had to be translated to percentage gas volume.

Chapter 6 : Biogas laboratory experiment – Results and Discussion

6.1. Results of analytical methods

6.1.1. TS and VS

The results can be seen in the table 6.1 bellow. The gr TS/l and gr VS/l contained in each bottle type represent the organic loading and can be seen in the same table. The full tables (tables A.1, A.2 and A.4) can be found in the appendix A.

Table 6-1. TS and VS of the different substrates.

Sample	% TS	% VS	gr TS/l	gr VS/l
BW	0.76	84.06	7.95	6.47
BW+KW	5.75	86.76	52.86	45.61
KW	18.60	89.37	168.52	150.33
IN	1.14	64.92	11.44	7.43

6.1.2. pH

The pH of the BW sample was 7.8, 4.5 for the BW+KW sample, 3.7 for the KW sample and 8.4 for the IN sample. The pH of the BW+KW and KW mixtures was quite low. Consequently, the pH of these samples had to be adjusted with the addition of base (5M N2OH) (table B.2 in the appendix B). In the cases that the pH of a sample was over 8, it was not adjusted because pH was expected to fall in the desired range during the anaerobic digestion process.

The pH of the new set of BW+KW samples that was prepared had pH of BW+KW was measured to be 4.11 and was adjusted to 8.2 by adding 5M NaOH. After the addition of the IN that had a pH value of 7.85, the final pH of the mixture was 7.97. The pH of the KW was measured to be 4.05 and was adjusted to 8.6 with the addition

of 5M NaOH. After the addition of the IN sample mentioned above the final pH of the mixture was 8.25. Full table (B.3) can be found in the appendix B.

6.2. Results of experimental methods

The results of the experiment are presented in the following table 6.2. A more thorough analysis of the results is presented in the following paragraphs. The tables containing the daily calculations can be found in appendix C.

Table 6-2 . Results of biogas experiment.

		gr TS / l	gr VS/ l	CH4 %	CH4 %	Biogas yield (ml/ gr VS added)	Biogas yield (ml/ gr VS added)	Methane yield (ml/ gr VS added)	Methane yield (ml/ gr VS added)
Sample	No.			day 15	day 30	day 15	day 30	day 15	day 30
BW	I	7.96	6.47	64.55	80.90	223.52	383.42	144.27	310.17
	II			62.39	77.69	214.24	367.08	133.66	285.20
	III			62.24	79.78	216.01	364.43	134.43	290.74
	avg.			**63.06**	**79.46**	**217.92**	**371.64**	**137.45**	**295.37**
BW+KW set II	I’	52.86	45.61	23.15	32.77	73.29	81.13	16.97	26.58
	II’			21.99	30.92	71.54	78.93	15.73	24.40
	III’			23.71	30.26	72.23	79.81	17.13	24.15
	avg.			**22.95**	**31.32**	**72.35**	**79.96**	**16.61**	**25.05**
KW set II	II’	49.97	44.39	5.19	61.78	65.55	92.52	3.40	57.19
	III’			9.29	61.20	68.29	88.50	6.34	54.21
	avg.			**7.24**	**61.49**	**66.92**	**90.51**	**4.87**	**55.70**
IN	I	11.44	7.43	53.28	68.75	108.46	211.54	57.79	145.43
	II			46.85	69.25	115.38	218.85	54.06	151.56
	avg.			**50.07**	**69.00**	**111.92**	**215.19**	**55.92**	**148.49**

6.2.1. Black water (BW)

The process for the AD of the BW was carried out without problems. TS and VS content was 7.96 gr/l and 6.47 gr/l, which is low compared to the KW and the BW+KW samples. As shown in figure 6.1, a steady production of biogas was achieved with high methane content.

Biogas yield was 217.92 (ml/gr VS added) after 15 days and 371.64 (ml/gr VS added) after 30 days. Methane content was 63.06% after 15 days and 79.46% after 30 days. Methane yield was 137.45 (ml / gr VS added) after 15 days and 295.37 (ml/gr VS added) after 30 days.

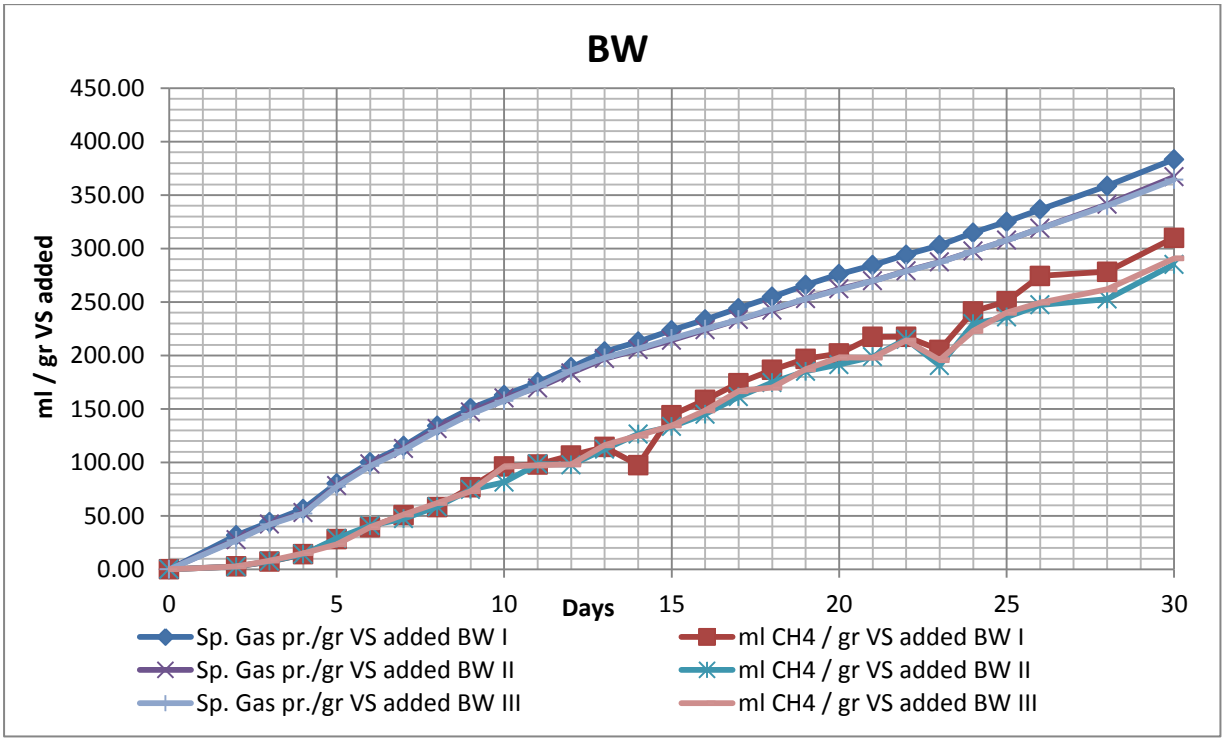

Figure 6.1. Black water - specific gas production vs CH4 production.

6.2.2. Black water and kitchen waste (BW+KW)

The BW+KW samples had to be adjusted for pH, as it has been described above, and exhibited a high initial gas production, which was mostly CO_2. TS and VS in the bottles were 52.86 gr/l and 45.61 gr/l respectively.

Biogas yield was 72.86 (ml/gr VS added) for set 1 and 72.35 (ml/gr VS added) for set 2 after 15 days and 79.96 (ml/gr VS added) for set 2 after 30 days, since set 1 sample was stopped at day 23 as mentioned. Methane content was 21.11% for set 1 and 22.95% for set 2 after 15 days and 31.32% for set 2 after 30 days. Methane yield was 15.38 (ml/gr VS added) for set 1 and 16.61 (ml/gr VS added) for set 2 after 15 days and 25.05 (ml/gr VS added) for set 2 after 30 days (figures 6.2 and 6.3).

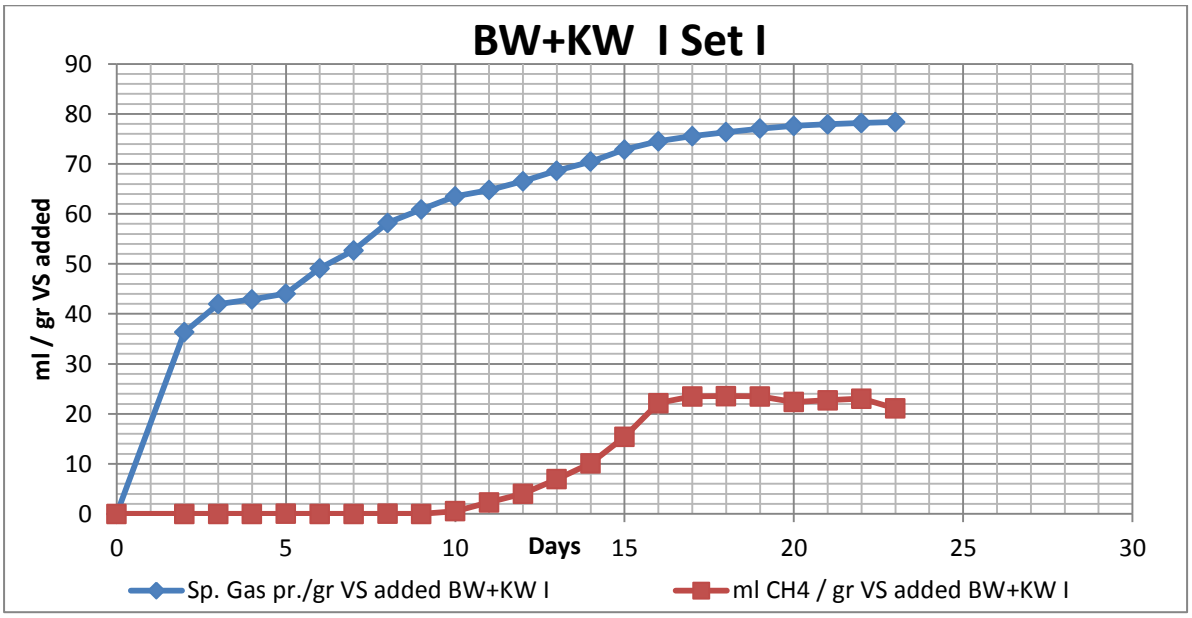

Figure 6.2. Black water and kitchen waste (set I) - specific gas production vs CH4 production.

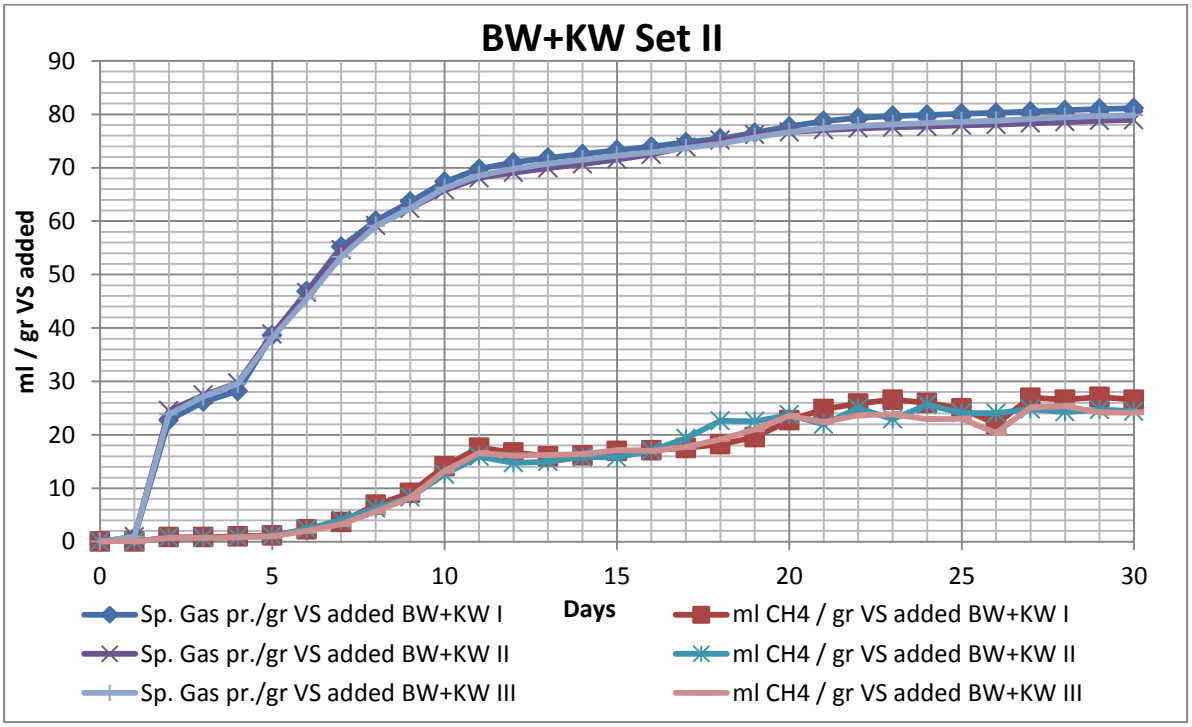

Figure 6.3. Black water and kitchen waste (set II) specific gas production vs CH4 production.

6.2.3. Kitchen waste (KW)

The diluted KW samples of the second set contained 49.96 gr TS /l and 44.36 gr VS/l and 15.36 gr VS added in the bottle. After the seeding on day 14, the new added VS amount in the bottles was calculated and found to be 15.68 gr (table A.6 in appendix A). Biogas yield was 66.92 (ml/gr VS added) after 15 days and 90.51 (ml/gr VS added) after 30 days. Methane content was 7.24% after 15 days and 61.49% after 30 days. Methane yield was 4.87 (ml/gr VS added) after 15 days and 55.70 (ml/gr VS added) after 30 days (figure 6.4).

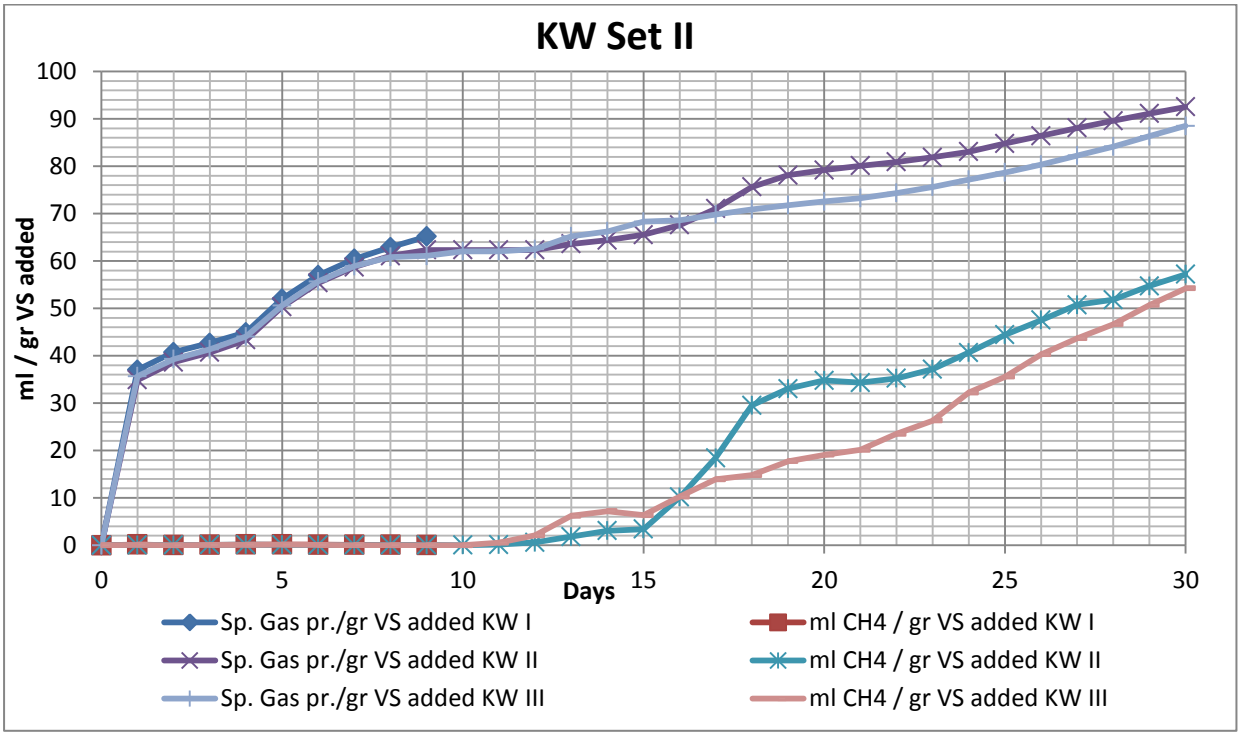

Figure 6.4. Kitchen waste (set II) - specific gas production vs CH4 production.

6.2.4. Inoculum (IN)

TS and VS content of he IN samples was 11.44 gr/l and 7.45 gr/l respectively. The IN sample was proved to be quite active.

Biogas yield was 111.92 (ml/gr VS added) after 15 days and 215.19 (ml/gr VS added) after 30 days. Methane content was 50.07% after 15 days and 69.00% after 30 days. Methane yield was 55.92 (ml/gr VS added) after 15 days and 148.49 (ml/gr VS added) after 30 days (figure 6.5).

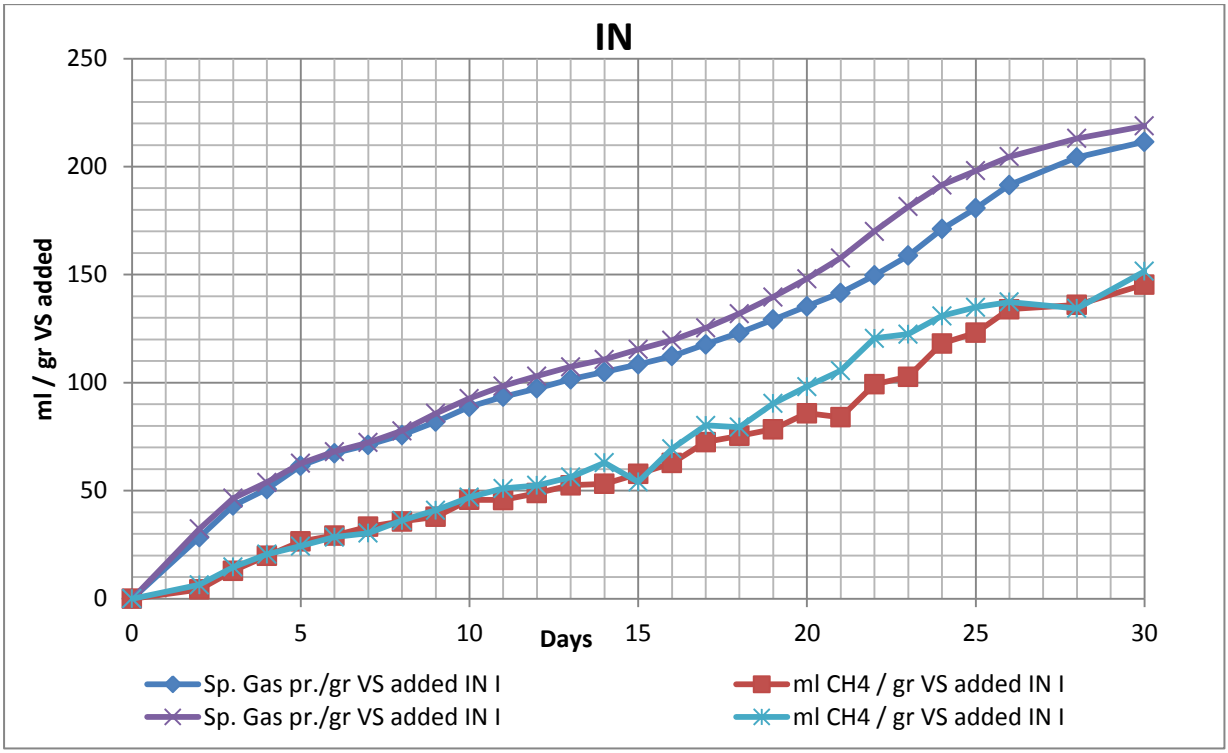

Figure 6.5. Inoculum - specific gas production vs CH4 production.

6.3. Discussion

6.3.1. Gas production

The total gas produced by KW and BW+KW samples was very high, as seen in figure 6.6 and was mainly composed of CO_2. This is attributed to the high organic loading of these samples. The results for the KW and BW+KW samples cannot be considered representative, since methane production was inhibited and their biomethanation was incomplete.

Out of the three samples, after the 30 days incubation period, BW had the highest biogas yield per VS added and the highest methane content per gr VS added, which in fact was much higher compared to that of the BW+KW and KW samples (figures 6.7 and 6.8).

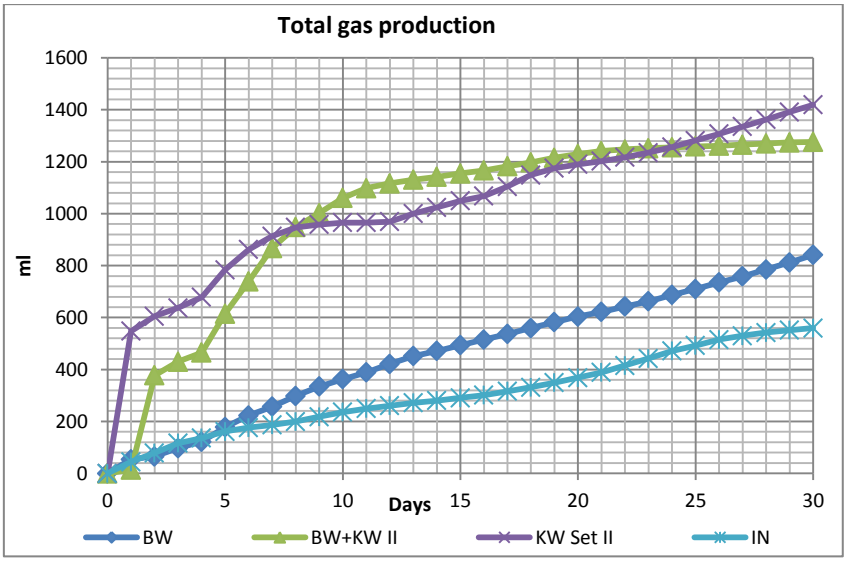

Figure 6.6. Total gas production.

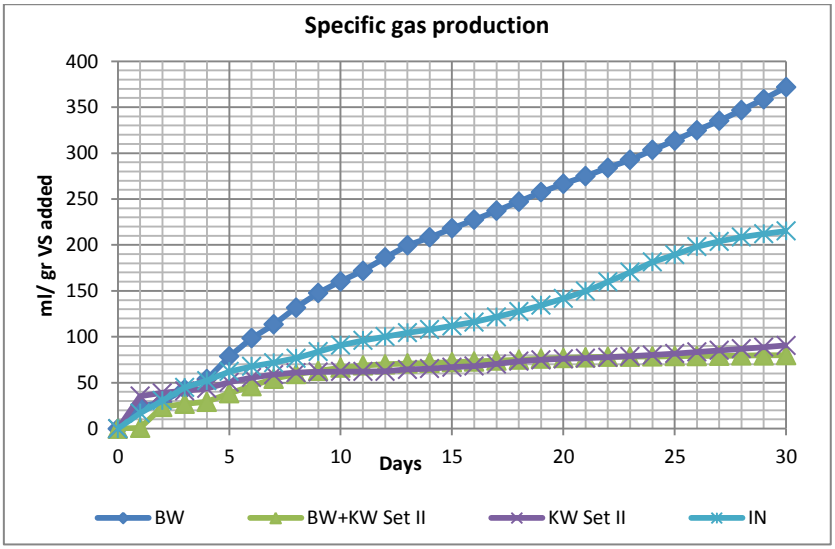

Figure 6.7. Specific gas production.

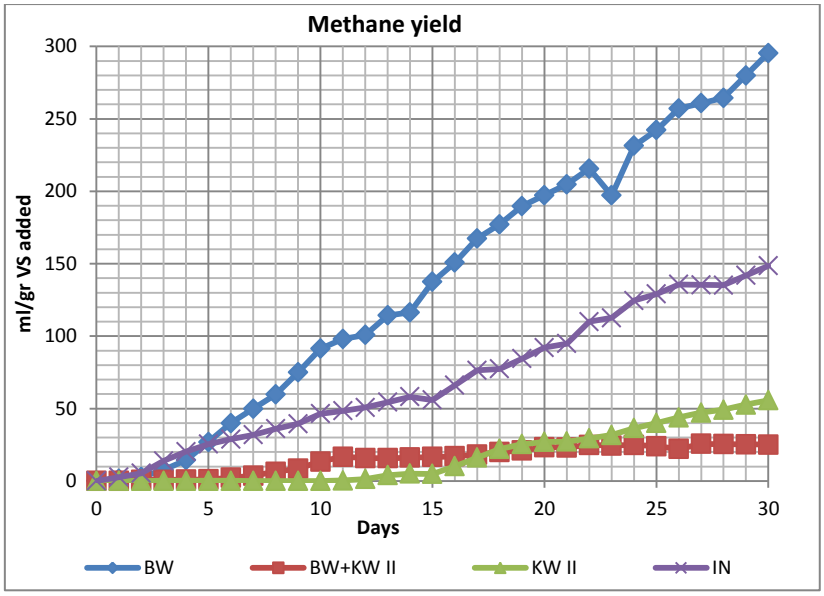

Figure 6.8. Methane yields.

It can be seen in figures 6.5 to 6.8 that the IN sample used that there was significant gas production to be attributed to it, which means it was not fully degraded. As a consequence, it is difficult to make the correction of the 30 days estimated methane potential of the samples. The IN ideally should have been pre-incubated until no significant gas production is observed (Angelidaki, Alves et al. 2009). So, it has to be highlighted that the above and the following estimated numbers for gas and methane production represent the mixed sample and inoculum substrates and the actual yields of the pure samples is less.

BW

The 30 days methane yield of the BW samples was 295.37 ml/gr VS added. Keeping in mind that the actual potential of the pure BW sample is a bit lower, the amount is comparable to the findings of Rajagopal, Lim et al. (2013), who conducted BMP assays using brown water samples from 2 l flush source separation toilets with 3.8 g VS/l and found the 30 days methane yield to be between 260 and 300 ml/gr VS added (Rajagopal, Lim et al. 2013). Other studies have found the methane yield of BW to be 209 l/kg COD in a mesophilic CSTR with 20 days HRT (Wendland 2008) and 217 l/kg COD after a 42 days BMP assay (Gallagher 2010). Around the end of the incubation period (day 28) a sudden increase in the methane production is noted. This indicates that a longer incubation period would give a more complete idea regarding the methane potential of the BW sample.

KW

The 30 days methane yield of the KW samples was 55.7 ml/gr VS added. Gunaseelan (2004), who conducted 100 day BMP assays on substrates that can be put into the general category of kitchen waste (fruit and vegetable solid waste), found that the methane yield was between 180 and 730 ml/gr VS added for fruit waste and between 190 and 400 ml/gr VS added for vegetable waste. However it is highlighted that most of the methane yield was achieved between 40 and 50 days of fermentation (Gunaseelan 2004). It can be seen in the figure 6.4 that the methane production of the sample has a considerable upward trend starting from day 14 when seeding took place, thus indicating that a lengthier incubation period would be more appropriate in order to have a better estimation of the methane potential. Indeed, gas production of the KW samples was followed until day 61 in order to have an idea and was found to that total gas production was more than doubled (figure 6.9) and specific gas production found to be in average 203.3 ml/gr VS added (figures 6.10). Gas composition was not yet determined at the moment of the writing of the thesis. Considering that methane content for KW was 61.49% on day 30, the estimated methane potential on day 61 could be over 125 ml/gr VS added. This illustrates the fact that using KW as co-substrate is a very good measure for raising the biogas yield.

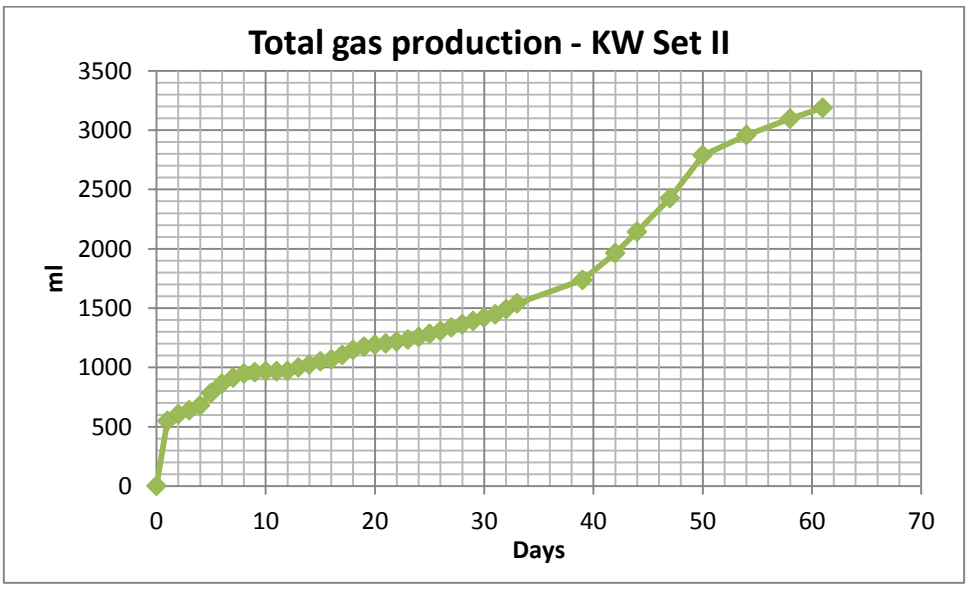

Figure 6.9. KW Set II - Total gas production

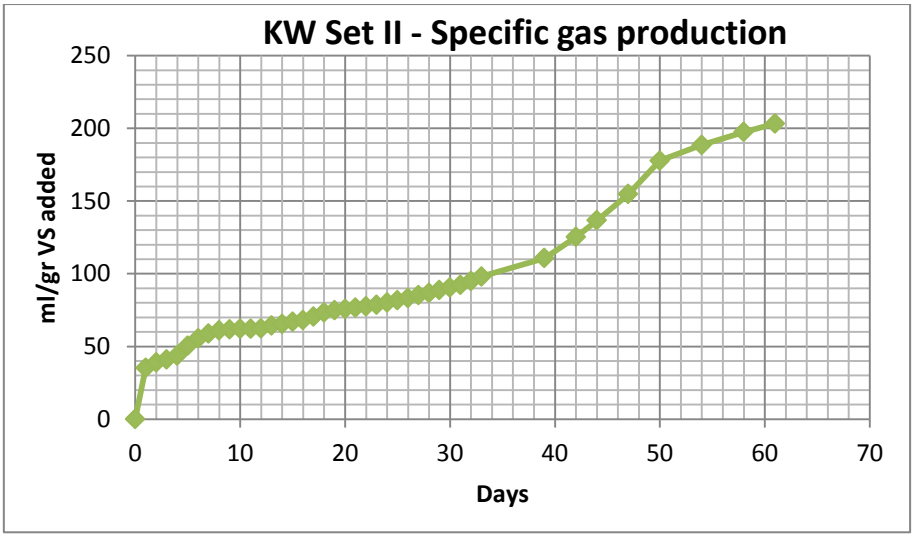

Figure 6.10. KW (Set II) - Specific gas production until day 61.

Other studies regarding the methane potential of kitchen waste or general food waste substrates found to be between 400 to 420 ml/gr VS added after a 30 days BMP assay (Rajagopal, Lim et al. 2013), 435 ml/gr VS added after 28 days of digestion in thermophilic lab scale experiment at 50^{o}C .(Zhang, El-Mashad et al. 2007). The

BW+KW

The 30 days methane yield of the BW and KW mixture was 25.05 ml/gr VS. In literature it has been repeatedly shown that the co-digestion of BW and KW offers significant improvements, especially regarding the methane yield (Kujawa-Roeleveld, Elmitwalli et al. 2006, Wendland, Deegener et al. 2006, Luostarinen and Rintala 2007). Namely, according to Wendland (2008) the addition of kitchen refuse to the BW substrate results to a significant increase of methane production (Wendland 2008) and Rajagopal, Lim et al. (2013), in the same report referred above, found that co-digestion doubled the methane yield. The methane yields reported are 255 l/kg COD added and 540-590 ml/gr VS added respectively. There was an attempt to regenerate gas production in the second set of BW+KW with pH adjustment at the end of the 30 day period that was unsuccessful. Seeding the samples could restart the process, as happened with the second set of KW samples, though there was not enough time to do so.

6.3.2. Influence of organic loading

High initial organic loading of the KW samples had a negative effect. The reasons are mentioned in the theory part. The TS content of the new set of KW samples was 49.98 gr/l, while the VS content was 44.39 gr/l. Zhang, El-Mashad et al. (2007) used KW samples with significantly lower concentrations, 6.8 gr VS/l and 10.5 gr VS/l (Zhang, El-Mashad et al. 2007). Cho, Park et al. (1995) used KW samples with 4, 10 and 50 gr VS/l. The 10 gr VS/l sample was initially inhibited due to low pH in the initial stage of the process, however in time the methane bacteria got acclimated and methane production was achieved. The 50 gr VS/l sample was also inhibited, but did not recover because of the excessive acidification in the reactor (Cho, Park et al. 1995).

6.3.3. Influence of pH

The effect of mixing the BW+KW samples with the inoculum prior to pH adjustment is apparent in the figures 6.2 and 6.3. Methane production got delayed in the first set. In the first set of BW+KW samples, methane production started after 10 days, while in the second at 5 days. However, the reason might also have to do with the fact that the first set of samples were kept more days in room temperature with no shaking. After 16 days in the first set and after 11 in the second set, gas production deteriorated and consequently methane content was kept from being raised, falling to almost zero. The pH of the second set of samples was measured at the end of the 30 day period and found to be 5.99 in average, which indicates that pH drop might be the reason of the gas production inhibition.

On the 9^{th} day pH was measured and adjusted for the second set of the KW samples. The opening of the bottles caused a disturbance to the AD process of the samples, as illustrated in figure 6.4. In fact the drastic raise of pH of the KW I' damaged the AD process of the sample and therefore it was aborted since there was no sign that gas production will recover. On day 14 the bottles KW II' and KW III' were seeded with 20 ml of IN in order to ensure gas production. It can be seen in the graph that gas production did start and continued until the end of the 30 day period.

Throughout the process, the pH of the BW+KW and KW mixtures had an inhibiting effect. In the course of the acidogenesis phase, pH drops drastically and in many cases the sample cannot recover. According to Wang, Odle et al. (1997) pH has a great significance when it comes to determining toxicity in food and vegetable waste. The reason is that a small drop of pH causes the concentration of the undissociated form of VFAs (undissosiated acetic, propionic, isobutiric and butyric acids) to rise, thus exerting toxicity and inhibiting the AD process (Wang, Odle et al. 1997). The inhibitory effect of the VFAs is mentioned also by Cho, Park et al. (1995). In their study they found out that the digestion of mixed food waste with high initial loading was inhibited because of low pH caused by the VFAs produced at the initial stage of the process (Cho, Park et al. 1995).

When gas production was slowed down or stopped, the bottles were opened for measuring and adjusting pH. When needed, in the case of the KW samples, the bottles were seeded with IN to force the process to start again. Chynoweth, Turick et al. (1993) suggest that increasing the inoculum to feed ratio is recommended in order estimate the maximum rate of methane production of some types of substrates (Chynoweth, Turick et al. 1993).

Lim (2011) who conducted BMP assays to similar substrates (brown water (B), food waste (F) and a mixture of both) in four different hydraulic loadings, followed the fate of pH of the samples during the process. The results of his work can be seen in the above graphs (figure 6.11). The rapid pH drop during the first days of digestion is obvious in the figure and especially dramatic for the food waste sample 4 which had the highest loading.

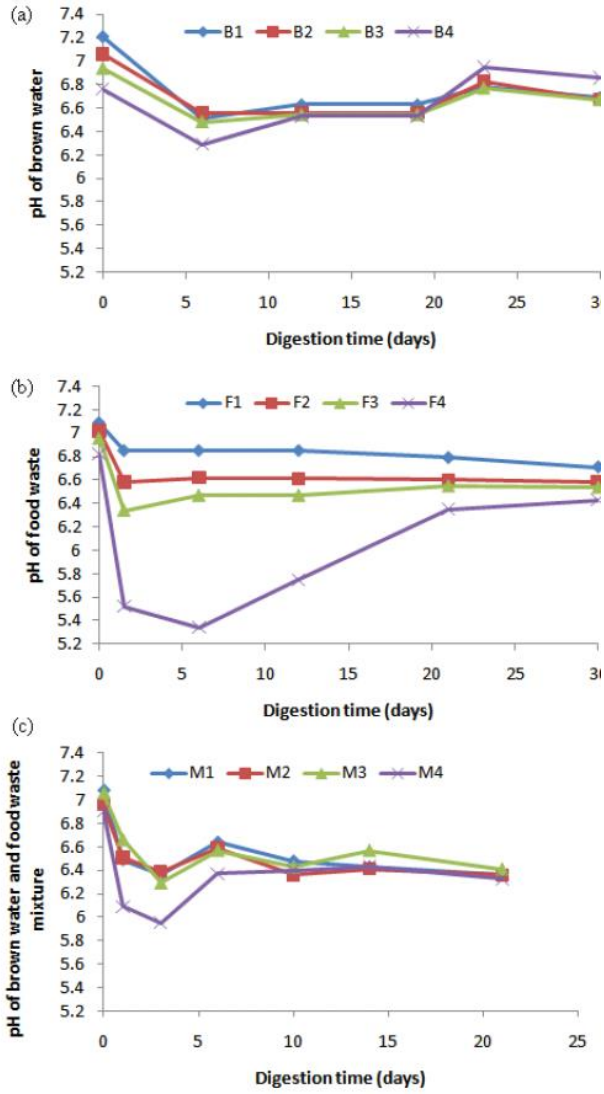

Figure 6.11. . pH of brown water, food waste and a mixture of both vs digestion time (Lim 2011).

Chapter 7 : Conclusion

Biogas production from pit latrine, kitchen and farm waste is a very good option for MCF Yatta. The available resources have a significant biogas potential that was estimated to be 7877 m^3/year or 21.58 m^3/day, assuming 60% methane content. The maximum energy equivalent of the estimated biogas potential is 184.3 GJ. Considerable financial benefits are involved. Part of the farm's energy needs, especially for cooking or lighting, can be covered. In addition, side benefits like the use of the biogas slurry as fertilizer and improved waste management and on-site sanitation are equally important.

It has been established that biogas production is promoted by the Kenyan Government, international organizations take action in designing the system and there are local especially trained masons that can be hired to construct the bioreactor. Given the nature of MCF organization, external funding could be granted. The temperature conditions at MCF Yatta are favorable for anaerobic digestion and biogas production. Special attention should be given during the rain seasons, in order to avoid flooding of the system.

The biogas lab experiment revealed problems that might occur during anaerobic digestion of waste and have to do with high organic loading and acidity in the substrate. The black water sample produced 371.64 ml biogas/gr VS added with 79.46% methane content. Part of this amount is attributed to the inoculum, because it was not fully degrade. The kitchen waste and the mixture samples were inhibited because of high organic loading and pH drop.

Regular pH measurement and adjustment was required throughout the process. Seeding was necessary for the rejuvenation of the gas production. Different loadings of the substrates should have been tested in order to determine the optimal organic loading. The incubation period should be long enough for the he full degradation of the substrates and the estimation of their ultimate methane potential. Pre-incubation of the inoculum was required for the correct biogas potential estimation of the pure samples.

Chapter 8 : Future work

The next step of the thesis will be sizing and designing the proposed system and the choice of the location. The implementation of the system will introduce biogas technology to MCF Yatta. The fixed dome plant will serve as an example that can scale up. There are plans for expanding the educational and commercial activities that will raise the population of the site. The agricultural activities will also increase and there are plans of constructing a poultry slaughterhouse. This will result to far more waste produced at MCF Yatta. A more sophisticated bioreactor could be installed in the future for a more steady and efficient gas production and higher biogas yield. A training program for the appropriate operation and maintenance of the system can be set up with the support of the Kenyan Government, national academic and research institutions and international organizations like NCA.

On-site sanitation can be further improved by connecting all the toilets of the site into a digester that can be used as a pre-treatment unit. The replacement of the existing flush toilets with low flush toilets would be a recommended feature for system like this. The option of source separation can also be considered.

The determination of the chemical characteristics (TS, VS, COD) of the actual waste that is produced at MCF Yatta could offer a safer estimation of the biogas potential. A new biogas lab experiment can be conducted, using substrates from the site of MCF Yatta or with similar characteristics. Bigger lab scale reactors can be used this time and a longer incubation period.

Finally, biogas production at MCF Yatta needs to be realized in the context of the ongoing renewable energy project of the site, along with biomass production and solar energy utilization. Overall, MCF Yatta has the potential to become an example of sustainable energy production.

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Appendix A: Total solids and volatile solids measurement

Table A.1. TS calculation

				m0		m1	
Sample	Cup no.	Cup weight (gr)	Cup with sample weight (gr)	Sample weight (gr)	Cup with dry sample weight (gr)	Dry sample weight (gr)	**% TS (m1/m0)*100**
BW	1	287.4	635.02	347.62	290.12	2.72	0.78
	2	317.86	705.33	387.47	320.76	2.9	0.75
	3	288.68	679.57	390.89	291.57	2.89	0.74
	Avg.						**0.76**
BW+KW	4	291.3	516.55	225.25	304.27	12.97	5.76
	5	280.97	500.24	219.27	293.57	12.6	5.75
	6	282.41	485.11	202.7	294.03	11.62	5.73
	Avg.						**5.75**
KW	7	123.85	213.33	89.48	140.35	16.5	18.44
	8	117.65	218.4	100.75	136.59	18.94	18.80
	9	118.87	233.25	114.38	140.09	21.22	18.55
	Avg.						**18.60**
IN	10	110.74	262.36	151.62	112.57	1.83	1.21
	11	119.4	263.42	144.02	120.86	1.46	1.01
	12	111.59	259.21	147.62	113.38	1.79	1.21
	Avg.						**1.14**

Table A.2. VS calculation

		m0'	**m1'**		**m2**		
Sample	Cup no.	Cup weight (gr)	Cup with sample weight (gr)	Sample weight (gr)	Cup with dry sample weight (gr)	Dry sample weight (gr)	**% VS ((m1'-m2)/(m1'-m0'))*100**
BW	1	13.506	13.788	0.282	13.548	0.042	85.11
	2	13.177	13.735	0.558	13.263	0.086	84.59
	3	13.61	14.198	0.588	13.713	0.103	82.48
	Avg.						**84.06**
BW+KW	4	13.357	14.829	1.472	13.7	0.343	76.70
	5	13.327	14.903	1.576	13.472	0.145	90.80
	6	13.358	15.119	1.761	13.485	0.127	92.79
	Avg.						**86.76**
KW	7	13.21	16.829	3.619	13.558	0.348	90.38
	8	12.899	17.122	4.223	13.428	0.529	87.47
	9	13.715	18.78	5.065	14.208	0.493	90.27
	Avg.						**89.37**
IN	10	13.51	14.84	1.33	13.99	0.48	63.91
	11	13.18	14.27	1.09	13.55	0.37	66.06
	12	13.62	14.87	1.25	14.06	0.44	64.80
	Avg.						**64.92**

Table A.3. TS and VS determination after mixing with the samples with the IN

Sample	**TS**	
BW	(90% BW + 10% IN) TS %	**0.80**
BW+KW	(90% (BW+KW) + 10% IN) TS %	**5.29**
KW	(90% KW + 10% IN) TS %	**16.85**
	VS	
BW	(90% BW + 10% IN) VS %	**82.15**
BW+KW	(90% (BW+KW) + 10% IN) VS %	**84.58**
KW	(90% KW + 10% IN) VS %	**86.93**

Table A.4. Organic loading in each bottle

			%TS	**%VS**	**gr TS / 350ml**	**gr VS / 350 ml**	**grTS/L**	**grVS/L**
BW	BW	315	0.757	84.059	2.384	2.004		
	IN	35	1.144	64.922	0.401	0.260		
	Total	**350**			**2.784**	**2.264**	**7.955**	**6.468**
BW+KW	BW+KW	315	5.746	86.762	18.099	15.703		
	IN	35	1.144	64.922	0.401	0.260		
	Total	**350**			**18.499**	**15.963**	**52.855**	**45.608**
KW	KW	315	18.597	89.375	58.581	52.356		
	IN	35	1.144	64.922	0.401	0.260		
	Total	**350**			**58.981**	**52.616**	**168.518**	**150.332**
IN	IN	350	1.144	64.922	**4.005**	**2.600**	**11.444**	**7.430**

Table A.5. Organic loading of the new set of diluted KW samples

KW set II	**ml**	**%TS**	**%VS**	**gr TS / 350ml**	**gr VS / 350 ml**	**grTS/L**	**grVS/L**
IN	35	1.144	64.922	0.401	0.260		
KW	91.9	18.597	89.375	17.091	15.275		
Water	223.1						
				17.491	**15.535**	**49.975**	**44.385**

Table A.6. Organic loading of the new set of diluted KW samples after seeding with 20 ml of IN

KW Set II	**ml**	**%TS**	**%VS**	**gr TS / 370ml**	**gr VS / 370 ml**	**grTS/L**	**grVS/L**
IN	55	1.144	64.922	0.629	0.409		
KW	91.9	18.597	89.375	17.091	15.275		
Water	203.1						
				17.720	**15.683**	**50.629**	**44.810**

Appendix B: pH measurement and adjustment

Table B.1. pH of the pure samples

Sample	BW	BW+KW	KW	IN
pH	7.8	4.5	3.7	8.4

Table B.2. pH before and after adjustment after mixing with IN

Sample	Bottle	pH	pH adj.	Comments
BW	I	7.3		No adjustment needed
	II	7.4		No adjustment needed
	III	7.5		No adjustment needed
BW+KW	I	4.34	7.7	7 ml 5M NaOH added
	II	4.28	7.55	7 ml 5M NaOH added
	III	4.55	7.62	7 ml 5M NaOH added
KW	I	4.25	8.8	20 ml 5M NaOH added
	II	3.85	7.68	20 ml 5M NaOH added
	III	3.87	9	20 ml 5M NaOH added
IN	I	8		No adjustment needed
	II	8.43		No adjustment needed
	III	8.45		No adjustment needed

Table B.3. pH of the set II samples before and after adjustment prior to mixing with IN and after mixing with IN

Sample	pH	pH adj.	pH (adj.+IN)	Comments
BW+KW Set II	4.11	8.2	7.97	20 ml 5M NaOH added in 945 ml of sample + 100 ml IN
KW Set II	4.05	8.6	8.25	23 ml 5M NaOH added in1466 ml diluted sample + 163 ml IN
IN from bottle III	7.85			263 ml out of 350 ml used

Table B.4. pH of the KW Set II samples before and after adjustment on day 9

Sample	Bottle	pH	pH adj.	Comments
KW Set II	I’	5.76	10.2	6 ml 5M NaOH added
	II’	5.82	8.32	3 ml 5M NaOH added
	III’	5.56	7.75	3 ml 5M NaOH added

Table B.5. pH of the KW set II samples after adjustment and seeding on day 14

Sample	Bottle	pH	pH adj.	pH (adj + 20 ml IN)	Comments
KW Set II	II’	6.75	7.2	7.25	3 ml 1M NaOH added + 20 ml IN
	III’	6.4	7.2	7.23	6 ml 1M NaOH added + 20 ml IN

Appendix C: Experimental measurements

Table C.1. Experimental measurements for BW

	Gas volume ml			Pressure mbar			Total l			% CH4			% CO2		
Time and date	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
3/6/2013 - 14.32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4/6/2013 - 14.30	41	40	40	201	195	189	41	40	40	NC	NC	NC	NC	NC	NC
4/6/2013 - 20.21	12	16	15	NC	NC	NC	53	56	55	NC	NC	NC	NC	NC	NC
5/6/2013 - 10.45	0	0	0	5	0	0	53	56	55	NC	NC	NC	NC	NC	NC
5/6/2013 - 15.10	19	7	6	113	96	96	72	63	61						
6/6/2013 - 10.05	24	28	29	134	158	164	96	91	90	8.47	9.30	10.38	23.91	23.78	25.34
6/6/2013 - 13.45	4	5	5	48	56	58	100	96	95	16.46	17.88	19.38	29.36	29.36	28.74
7/6/2013 - 11.30	28	24	23	180	172	167	128	120	118	24.95	26.73	28.74	30.08	29.75	30.23
8/6/2013 - 15.00	54	57	57	275	284	281	182	177	175	35.10	37.04	30.23	32.34	31.22	25.92
9/6/2013 - 14.30	45	46	44	241	242	238	227	223	219	39.36	41.56	40.77	31.28	34.33	32.46
10/06/2013 - 10.40	34	33	34	187	184	184	261	256	253	44.09	41.92	45.83	34.84	32.90	35.00
11/06/2013 - 12.45	43	42	40	229	228	219	304	298	293	43.39	44.53	47.96	32.07	31.94	33.62
12/06/2013 - 12.06	37	35	36	198	186	191	341	333	329	51.00	50.75	50.33	34.94	34.56	33.64
13/06/2013 - 14.00	28	30	28	193	188	181	369	363	357	59.00	50.82	60.96	37.20	33.55	37.01
14/06/2013 - 10.30	27	21	30	190	168	217	396	384	387	56.14	58.07	56.91	34.81	36.74	34.41
15/06/2013 - 11.40	32	32	34	199	183	194	428	416	421	56.31	53.27	52.77	33.90	32.84	32.12
16/6/2013 - 12.30	33	30	27	174	161	159	461	446	448	56.23	57.02	58.66	33.55	34.11	34.64
17/6/2013 - 10.10	21	19	19	118	112	112	482	465	467	45.82	61.63	60.62	26.92	35.94	34.50
18/6/2013 - 11.25	24	20	22	126	117	117	506	485	489	64.55	62.39	62.24	34.38	34.41	34.16
19/6/2013 - 12.05	23	22	20	134	129	120	529	507	509	67.83	64.78	66.11	35.10	34.52	34.53
20/6/2013 - 11.10	24	22	20	132	124	122	553	529	529	71.28	69.09	71.33	34.93	35.87	36.37
21/6/2013 - 12.35	24	20	23	128	121	123	577	549	552	73.22	72.09	69.72	34.61	35.48	34.30
22/6/2013 - 13.00	25	24	21	135	131	125	602	573	573	74.08	73.18	73.90	33.28	34.58	34.61
23/6/2013 - 13.40	23	21	19	126	119	117	625	594	592	73.14	73.01	75.74	31.42	33.24	33.81
24/6/2013 -	19	17	19	109	104	108	644	611	611	76.41	73.71	73.33	32.22	32.19	32.08

10.20															
25/6/2013 - 11.35	22	21	20	124	120	116	666	632	631	73.95	77.06	76.77	29.99	32.12	31.77
26/6/2013 - 10.10	20	19	19	119	111	112	686	651	650	67.75	66.27	68.15	26.25	27.11	27.53
27/6/2013 - 11.40	27	23	24	145	135	134	713	674	674	76.60	77.18	74.90	28.00	29.92	28.48
28/6/2013 - 11.25	23	23	23	129	126	122	736	697	697	77.11	76.65	77.98	27.20	28.30	28.68
29/6/2013 - 11.00	26	25	25	137	137	135	762	722	722	81.55	77.57	78.22	27.51	27.63	27.69
30/6/2013 - 11.30	24	24	22	133	134	129	786	746	744	0.00	0.00	0.00	0.00	0.00	0.00
1/7/2013 - 11.00	26	27	26	148	152	143	812	773	770	77.62	74.03	77.02	24.60	24.47	25.16
2/7/2013 - 12.20	27	28	26	147	153	147	839	801	796	0.00	0.00	0.00	0.00	0.00	0.00
3/7/2013 - 12.20	29	30	29	151	155	151	868	831	825	80.90	77.69	79.78	23.86	23.48	24.03

Table C.2. Experimental measurements for BW+KW set I

	Gas volume ml			**Pressure mbar**			**Total l**			**% CH4**			**% CO2**		
Time and date	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
3/6/2013 - 14.32	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
4/6/2013 - 14.30	177	160	176	845	760	830	177	160	176	NC	NC	NC	NC	NC	NC
4/6/2013 - 20.21	162	150	158	NC	NC	NC	339	310	334	NC	NC	NC	NC	NC	NC
5/6/2013 - 10.45	135	140	132	606	646	572	474	450	466	NC	NC	NC	NC	NC	NC
5/6/2013 - 15.10	106	128	118	521	629	566	580	578	584						
6/6/2013 - 10.05	45	39	49	301	288	267	625	617	633	0.00	0.00	0.00	68.49	82.68	81.15
6/6/2013 - 13.45	45	45	38	271	270	267	670	662	671	0.00	0.00	0.00	94.69	87.31	98.42
7/6/2013 - 11.30	15	19	26	140	137	167	685	681	697	0.00	0.00	0.00	101.50	103.82	95.11
8/6/2013 - 15.00	18	20	17	108	113	102	703	701	714	0.01	0.00	0.00	106.01	101.90	104.48
9/6/2013 - 14.30	81	82	80	412	426	411	784	783	794	0.00	0.00	0.00	115.76	115.92	109.90
10/06/2013 - 10.40	57	56	57	309	309	311	841	839	851	0.00	0.00	0.00	119.43	0.00	0.00
11/06/2013 - 12.45	88			389			929	839	851	0.02	0.00	0.00	118.68	0.00	0.00
12/06/2013 - 12.06	43			236			972	839	851	0.00	0.00	0.00	115.24	0.00	0.00
13/06/2013 - 14.00	42			227			1014	839	851	0.84	0.00	0.00	111.16	0.00	0.00
14/06/2013 - 10.30	20			177			1034	839	851	3.54	0.00	0.00	107.95	0.00	0.00
15/06/2013 - 11.40	28			168			1062	839	851	6.06	0.00	0.00	98.56	0.00	0.00

16/6/2013 - 12.30	34	178	1096	839	851	10.09	0.00	0.00	99.57	0.00	0.00
17/6/2013 - 10.10	29	163	1125	839	851	14.34	0.00	0.00	90.86	0.00	0.00
18/6/2013 -11.25	38	199	1163	839	851	21.11	0.00	0.00	84.17	0.00	0.00
19/6/2013 - 12.05	27	155	1190	839	851	29.73	0.00	0.00	86.76	0.00	0.00
20/6/2013 - 11.10	16	95	1206	839	851	31.09	0.00	0.00	83.71	0.00	0.00
21/6/2013 - 12.35	13	70	1219	839	851	30.85	0.00	0.00	81.12	0.00	0.00
22/6/2013 - 13.00	11	67	1230	839	851	30.49	0.00	0.00	79.34	0.00	0.00
23/6/2013 - 13.40	9	53	1239	839	851	28.83	0.00	0.00	74.79	0.00	0.00
24/6/2013 - 10.20	5	31	1244	839	851	29.18	0.00	0.00	75.82	0.00	0.00
25/6/2013 - 11.35	4	29	1248	839	851	29.47	0.00	0.00	76.37	0.00	0.00
26/6/2013 - 10.10	3	23	1251	839	851	26.91	0.00	0.00	69.63	0.00	0.00
27/6/2013 - 11.40	12	63	1263	839	851	8.35	0.00	0.00	21.27	0.00	0.00
28/6/2013 - 11.25	0	0	1263	839	851	9.59	0.00	0.00	24.45	0.00	0.00

Table C.3. Experimental measurements for BW+KW set II

	Gas volume ml			**Pressure mbar**			**Total l**			**% CH4**			**% CO2**		
Time and date	I'	II'	III'	I'	II'	III'	I'	II'	III'	I'	II'	III'	I'	II'	III'
12/6/2013 - 14.00	0						0	0	0	0	0	0	0	0	0
13/6/2013 - 11.00							0	0	0						
13/6/2013 - 11.17	12	15	15	58	82	77	12	15	12						
13/6/2013 - 14.00							12	15	24	1.69	1.74	1.93	12.86	12.81	13.84
14/6/2013 - 10.50	298	305	304	1219	1309	1284	310	320	334						
14/6/2013 - 14.00	53	71	61	282	359	311	363	391	697	3.66	3.19	2.95	61.63	67.90	64.73
15/6/2013 - 11.40	55	47	54	269	224	271	418	438	1115	3.19	2.61	2.65	77.59	78.04	79.02
16/6/2013 - 12.30	32	36	38	159	171	192	450	474	1565	3.54	2.81	2.75	89.67	85.30	83.44
17/6/2013 - 10.15	166	146	138	509	502	498	616	620	2181	3.05	2.75	2.68	102.23	100.56	100.06

18/6/2013 - 11.25	132	124	116	486	467	463	748	744	2929	4.88	5.09	4.41	103.95	106.01	105.96
19/6/2013 - 12.05	133	128	125	522	508	499	881	872	3810	6.71	7.42	6.13	105.68	111.47	111.86
20/6/2013 - 11.10	78	72	92	374	335	390	959	944	4769	11.47	10.61	9.56	107.98	107.24	103.25
21/6/2013 - 12.35	57	51	53	282	254	266	1016	995	5785	14.30	13.36	13.22	102.55	105.58	96.38
22/6/2013 - 13.00	59	55	61	303	275	305	1075	1050	6860	20.96	19.16	20.01	98.03	97.86	97.93
23/6/2013 - 13.40	39	37	37	196	183	190	1114	1087	7974	25.22	23.41	24.20	89.54	90.80	90.24
24/6/2013 - 10.20	19	16	20	102	95	110	1133	1103	9107	23.51	21.36	23.05	84.61	84.01	86.12
25/6/2013 - 11.35	14	13	15	84	81	90	1147	1116	10254	22.23	21.42	22.91	79.78	83.63	85.33
26/6/2013 - 10.10	11	12	12	73	72	75	1158	1128	11412	22.21	22.43	22.96	79.71	84.36	83.45
27/6/2013 - 11.40	12	14	12	77	88	77	1170	1142	12582	23.15	21.99	23.71	81.80	80.53	85.13
28/6/2013 - 11.25	10	15	10	68	92	71	1180	1157	13762	23.16	23.53	23.30	80.77	79.74	82.04
29/6/2013 - 11.00	13	22	13	76	118	79	1193	1179	14955	23.45	26.16	24.04	79.65	79.42	81.35
30/6/2013 - 11.30	11	21	13	71	113	86	1204	1200	16159	24.18	30.11	25.75	78.42	78.84	81.51
1/7/2013 - 11.00	18	16	19	100	90	111	1222	1216	17381	25.51	29.56	27.75	76.36	71.55	79.00
2/7/2013 - 12.20	18	8	16	104	55	102	1240	1224	18621	29.24	30.96	30.68	78.46	73.69	78.43
3/7/2013 - 12.20	17	6	12	99	46	73	1257	1230	19878	31.49	28.50	28.92	75.22	67.54	68.64
4/7/2013 - 13.30	9	5	6	66	40	52	1266	1235	21144	32.59	32.33	30.39	73.48	76.35	73.10
5/7/2013 - 12.45	6	3	5	46	33	42	1272	1238	22416	33.36	29.60	30.53	74.45	71.50	73.25
6/7/2013 - 13.50	3	2	4	33	26	36	1275	1240	23691	32.53	33.03	29.26	73.05	77.78	71.21
7/7/2013 - 14.50	4	4	4	31	53	36	1279	1244	24970	31.11	30.91	29.26	68.47	68.74	69.68
8/7/2013 - 14.30	2	2	3				1281	1246	26251	27.45	30.83	25.81	62.09	72.78	61.95
9/7/2013 - 12.40	4	4	5	37	34	41	1285	1250	27536	33.46	31.68	31.78	73.62	74.88	75.63
10/7/2013 - 13.20	4	4	5	35	34	38	1289	1254	28825	32.91	30.88	31.97	71.98	73.28	75.60

11/7/2013 - 15.20	4	4	4	34	33	36	1293	1258	30118	33.44	31.38	30.35	74.02	74.85	72.99
13/7/2013 - 12.30	4	4	4	33	31	35	1297	1262	31415	32.10	30.45	30.18	71.66	72.54	72.80

Table C.4. Experimental measurements for KW set II

	Gas volume ml			**Pressure mbar**			**Total l**			**% CH4**			**% CO2**		
Time and date	I'	II'	III'	I'	II'	III'	I'	II'	III'	I'	II'	III'	I'	II'	III'
12/6/2013 - 14.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13/6/2013 - 11.00	417	394	410				417	394	410						
13/6/2013 - 11.17	52	43	39	238	189	177	469	437	449						
13/6/2013 - 14.00	106	105	105	507	520	528	575	542	554	0.44	0.19	0.24	68.20	65.82	63.72
14/6/2013 - 10.50							575	542	554						
14/6/2013 - 14.00	58	58	56	314	298	314	633	600	610	0.01	0.10	0.00	84.54	91.87	92.09
15/6/2013 - 11.40	30	32	32	158	162	165	663	632	642	0.19	0.21	0.15	96.24	98.19	101.12
16/6/2013 - 12.30	35	41	42	166	197	210	698	673	684	0.32	0.29	0.23	102.99	108.86	109.49
17/6/2013 - 10.15	110	109	102	481	473	470	808	782	786	0.27	0.19	0.21	107.70	111.84	116.09
18/6/2013 - 11.25	77	78	79	359	346		885	860	865	0.20	0.11	0.12	113.16	114.19	117.25
19/6/2013 - 12.05	54	52	50	253	237		939	912	915	0.13	0.04	0.02	118.61	116.55	118.40
20/6/2013 - 11.10	38	37	30	188	170		977	949	945	0.16	0.10	0.00	110.80	113.71	114.64
21/6/2013 - 12.35	35	19	4	187	135	34	1012	968	949	0.03	0.09	0.00	113.39	114.63	79.17
22/6/2013 - 13.00	0	0	15	0	0	84	1012	968	964	0.04	0.01	0.00	1.02	36.13	43.70
23/6/2013 - 13.40	0	0	0	0	0	0	1012	968	964	0.15	0.19	0.83	0.87	35.57	45.82
24/6/2013 - 10.20	0	0	7	0	0	44	1012	968	971	0.18	0.93	3.31	0.00	38.87	57.47
25/6/2013 - 11.35		20	42		107	230		988	1013		2.86	9.49	0.00	46.65	58.81

26/6/2013 - 10.10	22	26		102	138		1010	1039		4.76	10.86		47.78	54.73	
27/6/2013 - 11.40	18	32		110	207		1028	1071		5.19	9.29		29.92	25.57	
28/6/2013 - 11.25	32	5		178	49		1060	1076		15.03	14.95		33.79	29.63	
29/6/2013 - 11.00	54	19		300	119		1114	1095		25.97	19.94		36.47	31.62	
30/6/2013 - 11.30	72	17		395	112		1186	1112		39.04	20.85		37.30	30.86	
1/7/2013 - 11.00	39	14		223	96		1225	1126		42.27	24.70		39.11	35.67	
2/7/2013 - 12.20	17	12		107	84		1242	1138		43.94	26.28		43.13	38.24	
3/7/2013 - 12.20	14	11		94	88		1256	1149		42.83	27.45		43.28	38.20	
4/7/2013 - 13.30	13	17		92	118		1269	1166		43.55	31.60		43.81	40.21	
5/7/2013 - 12.45	15	20		98	132		1284	1186		45.38	34.79		45.54	40.03	
6/7/2013 - 13.50	19	24		118	156		1303	1210		48.95	41.76		46.62	41.96	
7/7/2013 - 14.50	27	24		174	149		1330	1234		52.39	45.19		46.17	41.08	
8/7/2013 - 14.30	25	26					1355	1260		55.03	50.14		46.57	43.06	
9/7/2013 - 12.40	26	30		156	178		1381	1290		57.61	53.10		46.95	43.23	
10/7/2013 - 13.20	24	30		149	189		1405	1320		57.82	55.41		46.21	43.68	
11/7/2013 - 15.20	24	34		153			1429	1354		60.05	58.74		46.75	44.25	
13/7/2013 - 12.30	44	68					1473	1422		63.52	63.65		45.04	41.33	

Table C.5. Experimental measurements for IN

	Gas volume ml			**Pressure mbar**			**Total l**			**% CH4**			**% CO2**		
Time and date	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
3/6/2013 - 14.32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4/6/2013 - 14.30	22	26	23	115	139	106	22	26	23	NC	NC	NC	NC	NC	NC

4/6/2013 - 20.21	19	21	25	NC	NC	NC	41	47	48	NC	NC	NC	NC	NC	NC
5/6/2013 - 10.45	16	17	4	93	110	80	57	64	52	NC	NC	NC	NC	NC	NC
5/6/2013 - 15.10	17	20	25	99	117	139	74	84	77						
6/6/2013 - 10.05	30	31	33	162	160	172	104	115	110	15.06	19.86	16.90	18.19	17.76	16.02
6/6/2013 - 13.45	8	6	4	62	54	58	112	121	114	30.10	31.45	26.88	22.02	20.35	17.26
7/6/2013 - 11.30	20	19	20	139	117	141	132	140	134	39.08	38.16	36.99	21.74	20.78	19.45
8/6/2013 - 15.00	28	23	23	176	139	155	160	163	157	43.03	38.85	41.28	22.24	19.94	20.22
9/6/2013 - 14.30	15	14	14	86	82	83	175	177	171	43.46	41.91	44.16	22.02	20.77	20.95
10/06/2013 - 10.40	10	11	11	58	64	64	185	188	182	46.85	42.01	45.67	22.89	21.61	21.76
11/06/2013 - 12.45	12	14	10	73	80	76	197	202	192	47.21	46.60	49.48	22.77	21.86	22.16
12/06/2013 - 12.06	16	21	18	79	109	101	213	223	210	46.32	47.73	48.45	21.94	21.92	21.07
13/06/2013 - 14.00	18	18		91	102		231	241	210	51.54	50.67		23.44	22.11	
14/06/2013 - 10.30	12	15		92	102		243	256	210	48.86	51.85		22.64	22.98	
15/06/2013 - 11.40	10	12		61	79		253	268	210	50.22	50.90		23.24	22.84	
16/6/2013 - 12.30	11	11		71	73		264	279	210	51.68	52.44		23.88	22.96	
17/6/2013 - 10.10	9	9		53	55		273	288	210	50.66	56.87		23.49	24.98	
18/6/2013 -11.25	9	12		55	73		282	300	210	53.28	46.85		24.38	21.26	
19/6/2013 - 12.05	10	11		65	74		292	311	210	55.90	57.99		25.26	25.35	
20/6/2013 - 11.10	14	15		77	88		306	326	210	61.63	63.98		27.44	27.92	
21/6/2013 - 12.35	14	17		74	87		320	343	210	61.28	60.17		26.32	25.91	
22/6/2013 - 13.00	16	20		84	104		336	363	210	60.68	64.76		26.55	28.06	
23/6/2013 - 13.40	16	22		85	117		352	385	210	63.43	66.27		27.65	28.67	

24/6/2013 - 10.20	16	25	83	132	368	410	210	59.34	66.93	26.27	28.97
25/6/2013 - 11.35	21	32	115	169	389	442	210	66.37	70.91	28.04	30.29
26/6/2013 - 10.10	24	30	135	150	413	472	210	64.69	67.46	27.46	29.57
27/6/2013 - 11.40	32	26	166	140	445	498	210	69.03	68.36	28.83	30.44
28/6/2013 - 11.25	25	17	141	100	470	515	210	68.12	68.12	29.27	30.25
29/6/2013 - 11.00	28	17	147	92	498	532	210	69.95	67.11	30.64	30.52
30/6/2013 - 11.30	18	12	97	57	516	544	210				
1/7/2013 - 11.00	15	10	89	62	531	554	210	66.58	63.07	30.38	29.75
2/7/2013 - 12.20	10	8	67	45	541	562	210				
3/7/2013 - 12.20	9	7	63	53	550	569	210	68.75	69.25	31.46	31.73