

**DOMESTICATION OF TUBULAR POLYETHYLENE BIOGAS DIGESTER
TECHNOLOGY IN MALAWI**

MSC. (ENVIRONMENTAL SCIENCE) THESIS

EPHRON GAUSI

**UNIVERSITY OF MALAWI
CHANCELLOR COLLEGE**

MAY, 2015

**DOMESTICATION OF TUBULAR POLYETHYLENE BIOGAS DIGESTER
TECHNOLOGY IN MALAWI**

MSc. (ENVIRONMENTAL SCIENCES) THESIS

EPHRON GAUSI

BSc. (Environmental Science and Technology) - University of Malawi

Submitted to the Faculty of Science in partial fulfilment of the requirements for the
degree of Master of Science (Environmental Sciences)

UNIVERSITY OF MALAWI

CHANCELLOR COLLEGE

MAY, 2015

DECLARATION

I the undersigned hereby declare that this thesis is my own original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used acknowledgements have been made.

EPHRON GAUSI

Full legal Name

Signature

Date

CERTIFICATE OF APPROVAL

The undersigned certify that this thesis represents the student's own work and effort and has been submitted with our approval.

Signature: _____ Date: _____

Mlatho J.S.P., PhD (Senior Lecturer)

MAIN SUPERVISOR

Signature: _____ Date: _____

Mikeka C., PhD (Senior Lecturer)

MEMBER, SUPERVISORY COMMITTEE

COPYRIGHT

Copyright © 2014 by Ephron Gausi

All Rights Reserved

DEDICATION

I dedicate this work to all those who share my conviction that the education which is truly a key to national development is that which is able to effectively provide tangible answers and solutions to local development needs and challenges. This conviction has been the driving force behind this kind of work.

ACKNOWLEDGEMENTS

I first of all thank God for the gift of life and its inherent endowments which enabled me to have the quality of existence needed to carry out this work. Secondly I wish to thank the World Wildlife Fund-US and the Russell E. Train Education for Nature Fellowship Programme for the financial support which made this work possible.

I am very much indebted to my supervisors, Dr. J.S.P Mlatho and Dr. C.Mikeka for their distinguished guidance and support towards the success of this work. In particular I would like to thank them for their kindness and humility in allowing me to use their personal tools and equipment to do the desired plumbing, electrical and wood work of the project. I am also thankful to the staff in the Physics and Biochemical Sciences Department at the Malawi Polytechnic for lending me some of their instruments. The staff at Mzuzu University's Training Centre for Renewable Energy Technologies (TCRET) also shared with me valuable information about their work on biogas technology and linked me to Mr. Laurent Kumwenda who has constructed most of the fixed dome biogas plants available in Malawi. I thank them all. The staff at Leadership for Environment and Development Southern and Eastern Africa (LEAD SEA) needs also to be thanked for their space and storage drums at the Technology Development Centre study site. In particular, I would like to mention Mr. Welton Phalira, Mr. Gibson Mphepo, and Dr. D. Kafumbata for their brotherly mentorship and motivation.

I also acknowledge my undergraduate student friends, Bennet Chilalire and John Kabudula who were of great assistance during the construction, installation and operation of the experimental structures and including data collection. It is for this reason that they appear in most of the photographs contained in the thesis. I thank my family, relatives and friends for their moral and material support. In particular I would like to thank Mr and Mrs Major R.F. Gausi, and Mr and Mrs W.M. Gausi for allowing me to use their computers, digital camera and several other assorted personal items for my studies. Suppliers and sources of plumbing materials, polyethylene materials, feed materials and wood work and bamboo materials, I am grateful to them all. There are also many individuals who in one way or the other contributed to the success of the project but space does not permit to list all their names. I am never the less grateful for their contribution.

ABSTRACT

Effective development and promotion of biogas technology can offer numerous social, economic and ecological benefits to Malawi. However, development and adoption of biogas technology in Malawi has to a larger extent been constrained by locally unaffordable biogas digester designs. This study was conducted to assess the possibility of constructing low-cost tubular polyethylene biogas digesters locally and also to assess their performance under Malawian environmental and feed material conditions. The study showed that it was possible to construct tubular polyethylene digesters from locally available materials in Malawi. The constructed digesters were also able to produce biogas of flammable quality at local mean ambient temperatures of as low as 18 °C. The results of the study are generally encouraging because they indicate that tubular polyethylene biogas digester technology can be done in Malawi. However, effective domestication of the technology in Malawi will still require further development of local biogas technology research capacity.

TABLE OF CONTENTS

ABSTRACT.....	viii
TABLE OF CONTENTS.....	ix
LIST OF FIGURES	XII
LIST OF APPENDICES.....	XV
LIST OF ABBREVIATIONS AND ACRONYMS	XVI
CHAPTER 1	1
INTRODUCTION AND BACKGROUND	1
1.1 INTRODUCTION.....	1
1.2 RESEARCH PROBLEM.....	5
1.3 OBJECTIVES OF THE STUDY	6
CHAPTER 2	7
LITERATURE REVIEW	7
2.1 THEORY OF BIOGAS GENERATION.....	7
2.1.1 Anaerobic digestion process	7
2.1.1.1 Hydrolysis	8
2.1.1.2 Acidogenesis	8
2.1.1.3 Acetogenesis	8
2.1.1.4 Methanogenesis.....	9
2.1.2 Factors that affect anaerobic digestion process	9
2.1.2.1 Temperature	9
2.1.2.2 pH.....	10
2.1.2.3 Hydraulic retention time (HRT).....	10
2.1.2.4 Types and quality of substrates.....	11
2.2 GLOBAL OVERVIEW OF BIOGAS TECHNOLOGY.....	11
2.3 REGIONAL OVERVIEW OF BIOGAS TECHNOLOGY RESEARCH.....	13

WORK	13
2.4 BIOGAS TECHNOLOGY RESEARCH AND DEVELOPMENT IN MALAWI	13
CHAPTER 3	18
RESEARCH DESIGN AND METHODOLOGY	18
3.1 STUDY SITE.....	18
3.2 EXPERIMENTAL DESIGN OVERVIEW	19
3.3 SYSTEM SET UP.....	19
3.3.1 Digester design, construction and installation.....	19
3.3.2 Construction of the trenches and assembly of the polyethylene tubes	21
3.3.3 Construction of the greenhouses	23
3.3.4. Installation of polyethylene tubes.....	24
3.3.5. Charging of the digesters.....	25
3.4 DATA COLLECTION	26
3.4.1 Quantity of biogas produced per day	26
3.4.2 Methane Content	28
3.4.3 Gas pressure	29
3.4.4 Temperature	30
3.4.5 pH.....	32
3.4.6. Flammability test	33
3.5. DATA ANALYSIS.....	33
CHAPTER 4	34
RESULTS AND DISCUSSION	34
4.1 GAS GENERATION ONSET	34
4.2. BIOGAS PRODUCTION QUANTITY	36
4.3 METHANE CONTENT	39
4.4 TEMPERATURE BEHAVIOUR.....	41
4.5. PH INSIDE THE DIGESTERS	49

4.6 FLAMMABILITY TEST	50
4.7 PRESSURE.....	51
CHAPTER 5	52
CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS	52
REFERENCES	56
APPENDICES	64

LIST OF FIGURES

Figure 1: The main process steps of anaerobic digestion.....	8
Figure 2: Satellite imagery of Chancellor College Campus showing location of the Study site.....	18
Figure 3: Cross section diagram of a tubular polyethylene digester.....	20
Figure 4: Completed trenches inside a bamboo enclosure at the project site.....	22
Figure 5: Assembled polyethylene tubes hanged to the roof for safe keeping before installation.....	23
Figure 6: Cross section view of the greenhouse wood framework	24
Figure 7: Installation of the tubes into the trenches.....	25
Figure 8: The displacement apparatus used to measure amount of biogas produced.....	27
Figure 9: The device used for measuring content of methane placed inside a sampling bag.....	29
Figure 10: U-tube manometers connected to gas outlet pipe line.....	30
Figure 11: Internal digester temperature data download in progress.....	31
Figure 12: Digital temperature meter that was used to measure ambient and Greenhouse temperature.....	32
Fig. 13: Mean biogas production rates according to feed type and digester Operation environment.....	38
Figure 14: Biogas generation trends according to feed type and digester operation environment.....	39

Figure 15: Bar graph showing average methane content of biogas (Vol.-%) for the feed types and digester operation environment.....	41
Figure 16: Comparative ambient and hourly mean temperature trends inside and outside pig dung digesters operated inside greenhouse (GH) and without greenhouse (Open).....	45
Figure 17: Comparative ambient and hourly mean temperature trends inside digesters containing goat stomach wastes operated under greenhouse (GH) and without greenhouse (Open).....	46
Figure 18: Comparative ambient and hourly mean temperature trends inside digesters containing kitchen food wastes operated in the Open (Open) and greenhouse (GH) environment.....	48
Figure 19: Photograph showing the flame that was produced from burning of the biogas.....	50

LIST OF TABLES

Table 1: Time (days) taken by each digester feed type arrangement to start showing signs of gas production.....	35
Table 2: Summary of the amount of biogas production per feed type and operation environment.....	36
Table 3: Mean temperatures inside the digesters according to type of feed material and environment under which it was operated.....	41
Table 4: Results of univariate analysis of variances of the hourly mean internal digester temperature with respect to feed type and environment.....	42
Table 5: Mean pH values.....	49

LIST OF APPENDICES

APPENDIX A1: GAS PRODUCTIONA DATA.....	64
APPENDIX A2: pH DATA.....	65
APPENDIX A3: AMBIENT AND GREENHOUSE TEMPERATURE DATA.....	66
APPENDIX A4: DIGESTER PERFORMANCE DATA RECORDING FORM DESIGN.....	75

LIST OF ABBREVIATIONS AND ACRONYMS

APHA	American Public Health Association
ANOVA	Analysis of Variance
ASBR	Anaerobic Sequencing Batch Reactor
CARMATEC	Centre for Agricultural Rural Mechanization and Technology
CSTR	Continuously Stirred Tank Reactor
EAD	Environmental Affairs Department
ETHCO	Ethanol Company
FAO	Food and Agricultural Organization
GoM	Government of Malawi
HRT	Hydraulic Retention Time
LEAD SEA	Leadership for Environment and Development Southern and Eastern Africa
MIRTDC	Malawi Industrial Research and Technology Development Centre
NAPA	National Adaptation Programmes of Action
NSEOR	National State of Environment and Outlook Report
PFR	Plug Flow Reactor
PVC	Poly Vinyl Chloride
SPSS	Statistical Package for Social Scientists
TCRET	Training Centre for Renewable Energy Technologies
TPAD	Temperature Phased Anaerobic Digestion
TPD	Tubular Polyethylene Digester
UASB	Up-flow Anaerobic Sludge Blanket
UNDP	United Nations Development Programme
WHO	World Health Organization

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

Renewable sources of energy are an indispensable ingredient to sustainable social and economic development and no country can achieve sustainable development without ensuring adequate access to energy services for a broad section of its population (Stout and Best, 2001; Flavin and Aeck, 2010). Energy propels the development activities of a country and when it is renewable the greater the assurance of the continued availability of such services for development. Secondly, production and utilization activities of most renewable sources of energy are less harmful to the environment hence ensuring continuous availability of critical development resources and services provided by the environment.

Malawi is well endowed with a variety of renewable energy resources such as solar radiation and hydro power. However full potential of the renewable energy subsector remains far from being realised due to several structural, operational and institutional challenges. Even in cases where energy (in form of solar or hydroelectricity) is made available, it is not affordable by most households especially in rural areas (Government of Malawi (GoM), 2009a). As a result, most households that have electricity mostly use it for lighting and not cooking due to its prohibitive cost (GoM, 2009a). Solar energy is also not used for cooking in Malawi (GoM, 2009b).

The scenario just described has led to overdependence on firewood and charcoal as a primary source of energy. Current statistics indicate that more than 96 % of Malawians depend on firewood and charcoal for their domestic energy requirements (GoM, 2009c). In particular, about 99.7 % of the rural population depend on solid fuels such as firewood, charcoal and crop residues (GoM, 2009a). In addition, it is estimated that by 2015, almost the whole population will likely be using solid fuels (GoM, 2009a). This will be against the Millennium Development target of eliminating dependence on solid fuels by 2015. Solid fuels include coal, wood, charcoal, crops or other agricultural wastes, dung, shrubs, grass and straw (World Health Organisation (WHO, 2005).

Overdependence on solid fuels such as firewood, charcoal and crop residues has several disadvantages. Firstly, dependence on biomass sources for indoor cooking especially among rural households increases the risk of exposing children to pneumonia and other acute lower respiratory infections (ALRIs) and lung cancer among adults of over 30 years old (Rehfuess, 2006). In Malawian households, levels of particulate matter higher than those recommended by WHO have been reported (Fullerton et al., 2009).

Heavy reliance on firewood and charcoal has also been one of the major causes of deforestation in Malawi (GoMa, 2010; Kambewa et al., 2007). Among other things, deforestation has contributed to firewood scarcity resulting into a situation where women and girls walk longer distances to fetch firewood and in the process waste time that could be engaged in other critical personal and community development activities (GoM, 2010). Secondly, when firewood and charcoal are scarce and become

expensive, a greater proportion of household income is spent on meeting daily domestic cooking energy requirements. In cases where firewood cannot be fetched or bought, people are forced to resort to less efficient and lower grade biomass energy sources such as crop residues (Mlatho et al., 2005).

Deforestation is also said to contribute about 20% of carbon emissions responsible for global warming (Gullison et al., 2007). Climate Change is a reality in Malawi and it is negatively impacting the hydroelectric power generation in the country among other things (GoM, 2006). Unreliable hydroelectric power generation encourages reliance on fuel wood and charcoal as an alternative. In the end a vicious cycle is formed in which erratic hydro power supply encourages deforestation which in turn amplifies effects of climate change such as floods (Bradshaw et al., 2007) and feeds the global warming processes driving climate change forward. Effects of climate change also strain global and national economies as countries meet the costs of mitigation and adaptation to climate change (GoM, 2010).

Besides deforestation and climate change, poor waste management is also another major problem in the country (GoM, 1994; GoM, 2010). One contributing factor to continued existence of this problem is that most commonly used practices of handling waste in Malawi exhibit a culture of non/under-utilization of potential opportunities from wastes. For instance, a significant population of households in villages, towns and cities just dump most of their wastes along road sides or anywhere they can find space (GoM, 2010). Secondly, indiscriminate disposal of wastes into rubbish pits is also a common practice among households in both rural and urban areas (GoM, 2010). Human excreta are also just wasted into pit latrines and septic tanks. Wastes

from animal slaughtering houses and shelters are either buried in rubbish pits or just discharged into water courses. Moreover, animal manure is applied raw in crop fields. Most of these practices fall short of providing an avenue for adequate exploitation of opportunities from the waste such as composting. Lack of reduce, reuse and recycle elements in peoples waste generation and management behaviors leads to release of larger volumes of wastes which overstretch the capacity of local town and city councils to manage the waste. The result is poor service delivery which breeds unsanitary environmental conditions conducive for disease out breaks (GoM, 2010).

The existence of deforestation and climate change related problems in a country where a large proportion of population still relies on firewood and charcoal makes it even more imperative that appropriate alternative sources of energy should be relentlessly searched and promoted. In addition, an alternative source of energy capable of turning waste into opportunities for generating energy in a way that contributes to climate change mitigation would be more advantageous to Malawi. Biogas appears to be one such alternative energy source that has the potential to satisfy these conditions.

Biogas is a combustible mixture of gases that is produced when organic matter is degraded by complex biochemical processes in the absence of free molecular oxygen (Geraldi, 2003). It is mainly comprised of about 50-75 % methane (CH_4) and 25- 45 % carbon dioxide with minor traces of water vapour (2-7%); nitrogen (N_2) and oxygen (O_2) (less than 2%); and ammonia (NH_3), hydrogen (H_2) and hydrogen sulphide(H_2S) (less than 1 %), (Al Seadi et al., 2008). The methane is the component that gives biogas its flammable properties and as such biogas can be used for cooking, heating, lighting, electricity generation, and running refrigerators and internal

combustion engines (Karki, 2005). However, the major application of biogas in most developing countries is for domestic cooking (Fulford, 1988; Sasse et al., 1991; Karki, 2005).

Biogas technology has the advantage of offering more than one benefits at one and the same time. For instance biogas technology can contribute to prevention of emission of methane, a greenhouse gas which is 23 times more potent than carbon dioxide (Al Seadi et al., 2008), reduced deforestation through reduced dependence on wood fuel (Garfi et al., 2012), improved respiratory health and lives for women and children (Laurisden, 1998; Dohoo et al., 2013), improved waste management (McGarry and Stainforth, 1978; Werner et al., 1989) and improved agricultural productivity through use of effluent as fertiliser (Fullford, 1988; San Thy and Preston., 2003).

1.2 RESEARCH PROBLEM

Biogas technology has multiple potential benefits it can offer to Malawi if it is developed and effectively promoted. However its impact over the years has mainly been constrained by unaffordability of the conventional fixed dome and floating drum digester designs that have been used to promote the technology in Malawi. Tubular polyethylene biogas digester is a potential low-cost alternative digester design that can be used to promote biogas technology in Malawi. No attempt however has been made to understand, adapt and optimise its design and performance under local environmental conditions such as altitude and temperature. Secondly, pig manure, abattoir waste (animal intestine contents) and kitchen food remains are some of the potential locally available feedstock that can be used in tubular polyethylene digesters. The performance of these substrates in a tubular polyethylene biogas

digester under local conditions has never been studied and compared. To fill up these knowledge gaps, the present study was conducted.

1.3 OBJECTIVES OF THE STUDY

The overall purpose of the study was to assess the local construction feasibility and performance of tubular polyethylene digester technology under local climatic conditions and using locally available feed-material. Specifically, the objectives of the study were to:

1. Adapt the design of tubular polyethylene biogas digesters and construct the digesters using locally available materials
2. Asses the performance of the digesters in-terms of quantity and composition of biogas produced from locally available pig manure, animal stomach contents, and kitchen food wastes.
3. Understand temperature behaviour in the digesters when operated with and without greenhouse cover and also with three different types of substrates.

CHAPTER 2

LITERATURE REVIEW

This chapter starts with the theory of biogas generation and then gives an up to date overview of research work on biogas technology at global and sub-Saharan African regional levels. It ends with a detailed description of pieces of work done at local level. In general, substantial amounts of research studies on biogas technology have been done and documented at both global and regional levels compared to local level. This chapter is therefore more focused on the work that has been done locally so as to pioneer a more thorough documentation of local work that would form the foundation for future work.

2.1 THEORY OF BIOGAS GENERATION

2.1.1 Anaerobic digestion process

Anaerobic process of degradation of organic matter to produce biogas occurs in four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Al Seadi et al., 2008; Geraldi, 2006; Dana, 2010, Dublein and Steinhauser, 2008). Fig. 1 is a schematic diagram of the four main stages of the anaerobic process.

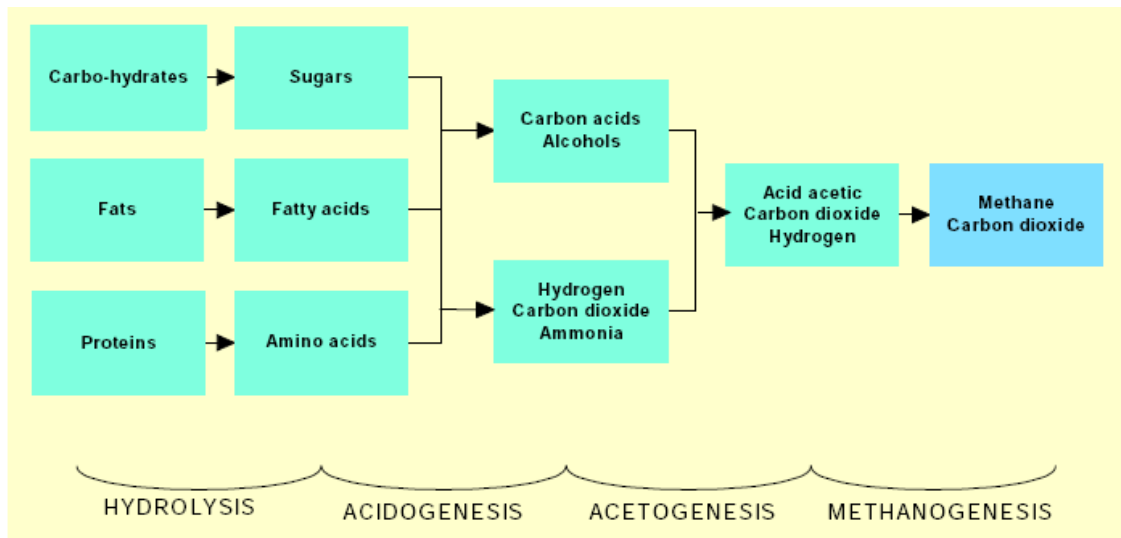


Figure 1: The main process steps of anaerobic digestion (Al Seadi et al., 2008)

2.1.1.1 Hydrolysis

During hydrolysis, large and complex molecular substances such as carbohydrates, lipids, nucleic acids and proteins are broken-down into smaller molecules such as glucose, glycerol, purines and pyridines by action of hydrolytic facultative and anaerobic bacteria (Geraldi, 2003). For instance cellulose is hydrolysed by *Cellulomonas* bacterium into several molecules of glucose.

2.1.1.2 Acidogenesis

In the acidogenesis stage, the acidogenic bacteria or acid-formers such as *Clostridium* convert simple sugars, amino acids, and fatty acids into acetate, carbon dioxide and hydrogen as well as into volatile fatty acids (VFA) and alcohols (Al Seadi et al., 2008).

2.1.1.3 Acetogenesis

During acetogenesis, acetogenic bacteria convert several of the fatty acids and alcohols produced in the acidogenesis stage to acetate, hydrogen, and carbon dioxide (Geraldi, 2006).

2.1.1.4 Methanogenesis

Finally, the acetate, carbon dioxide and hydrogen produced in the preceding stages are converted to methane and carbon dioxide by methanogenic bacteria in the methanogenesis stage. About seventy percent of the methane is formed from acetate and the remaining thirty percent comes from hydrogen and carbon dioxide (Al Seadi et al, 2008). Methanogenesis is a critical step in the entire anaerobic digestion process, as it is the slowest biochemical reaction of the process.

2.1.2 Factors that affect anaerobic digestion process

In general, the success of the anaerobic digestion process depends on several biotic and abiotic conditions. In particular, methanogenesis is severely influenced by substrate and operational conditions such as composition of feedstock; feeding rate, temperature, and pH. Digester overloading, temperature changes or large entry of oxygen can result in termination of methane production (Al Seadi et al., 2008).

2.1.2.1 Temperature

Activity of the types of organism involved in anaerobic digestion strongly depends on temperature. Most methanogenic microorganisms operate optimally at mesophilic temperatures of between 30°C to 42°C and only a few are thermophilic (43°C to 55°C) and psychrophilic (<20°C) (Dublein and Steinhauser, 2008, Al Seadi et al, 2008). It is generally important to keep temperatures constant however thermophiles are more sensitive to temperature variations than mesophiles.

2.1.2.2 pH

The pH in the digester environment is a very important parameter in the anaerobic digestion process. Enzymic activities of anaerobic microorganisms are strongly dependent on the pH in the digester. The pH also affects the dissociation of compounds such as ammonia, sulphide, and organic acids which influence the anaerobic process. Most anaerobic bacteria, including methane-forming bacteria, perform well within a pH range of 6.7 to 7.5 (Gerald, 2003; Dublein and Steinhauser, 2008). The pH in the digester is usually naturally maintained around a neutral point by action of the carbon dioxide/bicarbonate/carbonate and ammonia-ammonium buffer systems. A too strong acidification is avoided by the carbon dioxide/hydrogen carbonate/carbonate buffer system and a too weak acidification is avoided by the ammonia - ammonium buffer system.

2.1.2.3 Hydraulic retention time (HRT)

Hydraulic retention time (HRT) is defined as the average length of time the substrate is kept in the digester. Appropriate hydraulic retention time is important for two reasons. Firstly, it allows availability of adequate populations of microorganisms before they are washed out. Secondly, allows thorough digestion of the slow-degradable substrates. The hydraulic retention time HRT is correlated to the digester volume and the volume of substrate fed per time unit time. Choice of hydraulic retention time depends on the digestibility of the substrates, operation temperature, desired digester volume and quantity of substrates available to be loaded per day (Al Seadi et al, 2008). Typical HRT values for successful anaerobic digestion operated mesophillically range between 30 to 70 days (Karki, 2005, Luer, 2010).

2.1.2.4 Types and quality of substrates

In order to grow, microorganisms require both macro nutrients such as carbon, nitrogen, phosphorus and sulphur which are required in large quantities and micro nutrients such as iron, cobalt, nickel, selenium, molybdenum or tungsten which are required in minute quantities. These need not only to be available in the feedstock materials but also be in correct proportions (Gerardi, 2006).

2.2 GLOBAL OVERVIEW OF BIOGAS TECHNOLOGY

Nasir et al. (2012) provide a review of the work that has been done on anaerobic digestion of livestock manure for waste treatment and biogas generation purposes globally. They report that a variety of different operational conditions, various reactor configurations such as batch reactors, continuously stirred tank reactor (CSTR), plug flow reactor (PFR), up-flow anaerobic sludge blanket (UASB), anaerobic sequencing batch reactor (ASBR), temperature phased anaerobic digestion (TPAD), and continuous one- and two-stage systems, present a suitable technology for the anaerobic digestion of livestock manure waste. Furthermore, they give picture of the improvements that have happened in the understanding of the anaerobic process. They reveal that the focus of current work has been on the optimisation of the anaerobic digestion process so as to achieve such qualities as maximisation of methane yield, increased organic loading rate at reduced hydraulic retention times, effective transfer of active biomass in the digester, reduction of process energy and heat loss and achieving a reliable system with lowest installation and operation costs.

Rajendran et al. (2012) also provide a global review of household biogas digesters in which, from other studies, they summarize different aspects of the design and

operation of small-scale, household, biogas digesters covering different digester designs and materials used for construction, important operating parameters such as pH, temperature, substrate, and loading rate, applications of the biogas, the government policies concerning the use of household digesters, and the social and environmental effects of the digesters. They note that interest in biogas technology is growing slowly in many poor countries and effort should be made to increase the awareness and to introduce affordable and more efficient digesters tailored to take full advantage of the local possibilities in order to succeed.

In general, it is observed from the work by these groups of authors that more advanced research work on biogas technology has been in the developed countries of Europe and America. Secondly, the common application of biogas technology in these developed countries has been the large scale type either for treatment of large volumes of organic wastes from waste water treatment plants or commercial farms. Some large scale projects have also been undertaken solely for generation of electricity for sale. On the other hand, most of small-scale digesters have been concentrated in developing countries with India and China as leading countries accounting for the highest share. The primary purpose for these small scale digesters has been to provide energy. With the exception of the South East Asian, countries, there has generally been minimal research work on biogas technology and its application in most of the developing countries.

2.3 REGIONAL OVERVIEW OF BIOGAS TECHNOLOGY RESEARCH WORK

At regional level, Mshandete and Parawira (2008), provide an insight and update of the state of biogas technology research in some selected sub-Saharan African countries from peer reviewed literature. They highlight that the methane-producing potential of various agriculturally sourced feedstocks has been researched, as have the advantages of co-digestion to improve carbon-to-nitrogen ratios and the use of pre-treatment to improve the hydrolysis rates by some researchers in Nigeria, Tanzania, and Zimbabwe. They however lament that there appears to be little research in biogas technology in many sub-Saharan African countries in internationally peer reviewed literature. They also point out that biogas production from large quantities of agricultural residues, animal wastes, municipal and industrial wastes (water) appears to have potential as an alternative renewable energy for many African countries if relevant and appropriate research is carried out to adopt the biogas technology to the local conditions in African countries. They conclude by urging African scientists to carry out research in biogas technology to locally demonstrate the feasibility, application, and adaptation of this technology and help improve the quality of energy supply in their respective countries.

2.4 BIOGAS TECHNOLOGY RESEARCH AND DEVELOPMENT IN MALAWI

The multiple benefits that biogas plants can offer to Malawi seem to have been recognised early enough as evidenced by a biogas research study that was carried out as early as 1977/8 at the Department of Chemistry, Chancellor College (Malawi Industrial Research and Technology Development Centre (MIRTDC), 1996).

However due to loss of actual research project document, the exact objectives and the findings of the research could not be established. In general, typical scientific research literature on biogas technology in Malawi is scarce. This can be attributed to lack of local research work on the subject as well as poor documentation, storage and dissemination. Information on biogas technology in the country is therefore mainly obtained from some community and industrial projects initiated by private companies, government departments, academic institutions and organisations to demonstrate and promote biogas technology in Malawi. Kraemer, (1996), in the process of conducting a prefeasibility study on rural electrification from biogas in Malawi, documented most of the earliest community and industrial biogas promotion and dissemination projects that were initiated between 1991 and 1996.

With regard to household and community biogas demonstration projects, two conventional digester designs have been used in Malawi. These are the Chinese fixed dome design and the floating drum design (Kraemer, 1996; Tembo, 2010). The fixed dome plant basically comprises of an underground, closed, dome-shaped brick and reinforced concrete tank with an immovable, rigid gas-holder and a displacement pit (Fullford, 1988). The floating drum digester on the other hand consist of an underground cylindrical brick and concrete tank with an inverted metallic drum gas-holder which floats either directly on the fermentation slurry or in a water jacket of its own (Fullford, 1988; Karki, 2005).

These digester designs have their advantages such as longer lifespan and high and constant gas supply pressure (Rajendran et al., 2012). These advantages of the fixed dome and floating drum biogas digesters are however overshadowed by their high

construction cost and difficulty in installation and maintenance (Rodriguez and Preston, 1997). Experiences from various players working with these digester designs in Malawi have also revealed that they are expensive. This was first observed as early as 1996 by delegates to a national biogas forum that was organised by MIRTDC (MIRTDC, 1996). In trying to consider the type of biogas digesters suitable for Malawi it was noted that the fixed dome type of biogas plant was wasteful while the floating drum design was more expensive hence prohibitive (MIRTDC, 1996). More recently, the Test and Training Centre for Renewable Energy Technologies (TCRET) at Mzuzu University also has had similar experiences from its Choma-Chigwere Biogas Project in Mzuzu where construction materials alone for a 3m³ fixed dome digesters cost more than MK500, 000 (about US\$1539)(TCRET, 2012).

In Malawi, more than fifty percent of the population is still considered as poverty stricken (World Bank, 2012). Therefore a biogas digester investment worthy more than US\$1539, is too enormous for a typical Malawian rural household to afford. This partly explains why after more than two decades of efforts to demonstrate and promote biogas technology in Malawi using the conventional designs, only about 40 plants have been built (Tembo, 2010; Kumwenda, *pers. comm*), giving an average of about two biogas plants built per year. Secondly it is observed that of these, only about five were financed by users themselves. The rest were financed by grants from development partners. This observation ties in with experiences from most of the developing countries such as China, India, Nepal and Vietnam where they have had national biogas promotion programmes based on the fixed dome and floating drum digesters. In these countries, subsidies and loans were essential components of the programmes (Karki, 2005; Fullford, 1988). Subsidies are however unsustainable and

access to loans for small scale business in Malawi is already a challenge, let alone for biogas plant investment.

The economics of biogas are important because people will not use a new technology, however good, if it costs more than the alternatives (Fullford, 1988). It therefore appears that as long as the digester systems used for the promotion of biogas technology in Malawi remain unaffordable to ordinary Malawians, the potential of the technology to contribute to environmental sustainability among others will not be unleashed. One way of overcoming this barrier is to identify alternative low-cost designs suitable for Malawi. Among the potential alternative low-cost designs that can be demonstrated in the country is the tubular polyethylene digester design. The digester system uses thick tubular polyethylene material as main digestion vessel instead of concrete and brick masonry. This design was first developed in Colombia around the 1980s and has been demonstrated, used and improved in countries such as Vietnam, Ethiopia, Tanzania, Kenya, Zimbabwe, Bolivia, Peru, Ecuador, and Mexico (Rodriguez and Preston, 1997; Marti-Herrero, 2011; Marti-Herrero and Supriano, 2012; Furze, 2002). The polyethylene tubular digester technology is cheap and simple way to produce biogas for households in rural and urban areas and at both low and high altitude (Rodriguez and Preston, 1997).

Digester design parameters and performance among other things depend on factors such as temperature (Al Seadi et al., 2008) which vary from one place to another. This implies that to achieve optimisation; it is important that a generic digester design is adapted to particular conditions prevailing in particular country, region and locality. Design data and principles learned in a developed country are often misleading hence

techniques and design approaches need to be adapted to the local situation (Fullford, 1988). Regardless of this, no work has been done to demonstrate how the tubular polyethylene digester can be designed and be optimised under Malawian environmental and feed-material conditions.

Besides the low-cost digester systems, more alternative types of locally available feedstock need to be identified and demonstrated in order to facilitate the growth of biogas technology in Malawi. So far, cow dung and pig manure have been the main types of feed-materials used to operate biogas digesters in Malawi (Kraemer, 1996). Several potential alternative feed stocks for biogas production exist in Malawi. These include human excreta, abattoir wastes, food wastes, municipal wastes, industrial organic wastes as well as aquatic invasive species such as water hyacinth among others (Kraemer, 1996; Almoustapha et al., 2009; Elaiyaraju and Partha, 2011; Pound et al., 1981; Frost, 2011; Iyagba et al., 2009; Ghani and Idris, 2009). Of these, only few have been tested in Malawi. For instance, the Tanzanian Centre for Agricultural Rural Mechanisation and Technology (CARMATEC), successfully commissioned a floating drum biogas plant using human excreta from students toilets at Phwezi girls private secondary school in Rumphi district in 1997 (Phiri, *pers. comm*). The gas was used to prepare meals for students until in January 2009 when the plant stopped working due to dilapidation and detergent poisoning. The industrial biogas plant project by Ethanol Company (ETHCO) Limited at Dwangwa attempted to use wastes (Vinasse) from ethanol production process but was unsuccessful (Kraemer, 1996; Chakaniza, *pers. comm*). In general, however, it is observed that none of the locally available substrates has been used with tubular polyethylene digesters in Malawi hence their performance is unknown.

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

3.1 STUDY SITE

The study was carried out at the Technology Development and Learning Centre of Chancellor College in Zomba district at 15.3882° S, 035.33412° E and 898 m above sea level. Zomba experiences a tropical climate with three main seasons: cold-dry, hot-dry and hot-wet, ranging respectively from April to July, August to October and November to March. The hottest months are September, October and November, with average temperatures ranging between 28 and 30 degrees Celsius. June and July are the coldest months, with minimum temperatures as low as 10°C (Zomba District Assembly, 2009). The site was chosen because of easy monitoring of the digesters, adequate security of data collection equipment and proper building for the digesters.



Figure 2: Satellite imagery of Chancellor College Campus showing location of the study site.

3.2 EXPERIMENTAL DESIGN OVERVIEW

The study followed an in-situ experimental design approach in which three pairs of tubular polyethylene digesters of same design and size were constructed and installed within a similar microclimate environment (at the same site). One pair of the digesters was fed with pig dung, another pair with fresh goat stomach contents and the last pair with kitchen food wastes. One digester in each pair was enclosed in a movable greenhouse structure made from transparent polyethylene material. The experiment run for a period of three months during which data on the temperature inside the six digesters was collected at an hourly average using K-chrome thermocouples (± 1.1 °C) and an automatic data logger (Campbell Inc., CR10 model). Ambient temperature and the temperature inside the green houses were monitored at every hour each day for a period of one month using a handheld multi-meter (Brymen, TBM815 model). Volume of gas produced per day was monitored using a water-displacement based system that was improvised from 5-litre empty plastic cooking oil containers and 13-litre buckets. The content of methane in the produced biogas was analysed using the Dragger gas monitor (Dragger Safety AG & Co. KGaA, X-am 7000 model). The pH was measured using both bench (Metrohm, 827 pH Lab Model) and portable (Oakton, Eco-Testr pH2 model) digital pH meters. Gas pressure was measured using a hand crafted u-tube manometer. A flammability test was also carried out to see whether the gas that was produced was flammable and the quality of the flame.

3.3 SYSTEM SET UP

3.3.1 Digester design, construction and installation

This section explains the design, construction and installation of the digesters. The study used an improved tubular polyethylene digester design methodology by Marti-

Herrero and Supriano (2012). The methodology uses trench cross sectional area and optimisation of trench dimensions with respect to the bottom angles (α) of the side walls (A) of the trench and the relationship between length of the biogas bell (L_{bell}) and the top width of the trench (b) as shown in Fig. 3.

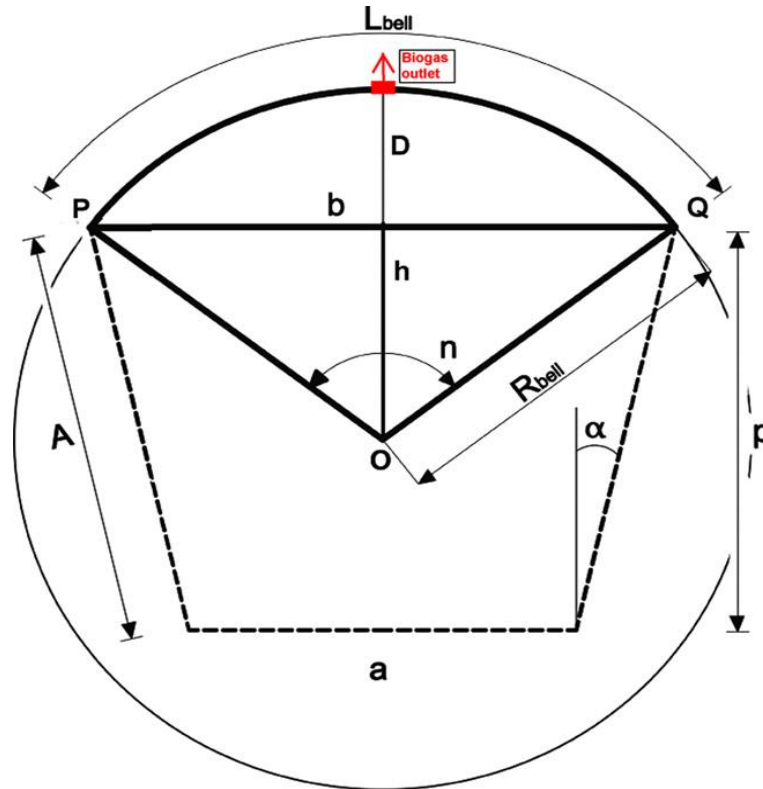


Figure 3: Cross section diagram of a tubular polyethylene digester (Marti-Herrero and Supriano, 2012)

This new methodology overcomes the problem of reduction in actual hydraulic retention times that was experienced with older designs whose liquid volume calculations are based on the circular cross sectional area of the polyethylene tube (Marti-Herrero, 2011).

Sizing of the digester was based on a daily substrate-water mixture loading volume and hydraulic retention time. The study used a daily fresh substrate loading rate of 5

kilograms per day and a retention period of 40 days as design criteria. This amount was chosen for easy collection, sorting and transportation of the substrates to the digester site. The retention period of 40 days was chosen because the digesters were expected to operate at local ambient temperatures of between 28 °C and 30 °C which are within the mesophilic temperature range of 20 °C – 45 °C (Al Seadi et al., 2008). The substrate-water mixing ratio of 1:3 was used to ensure fluency of slurry so as to prevent obstruction (Marti-Herrero and Supriano, 2012). The design daily substrate-water mixture loading volume (V_R) was found by multiplying the sum of substrate (R_s):water (R_w) mixing ratios by the design daily fresh substrate mass loading rate (M_s) and 1 L, assuming that 1 kg of the substrate was equal to 1 L of water as shown in equation (3.1).

$$V_R = (R_s + R_w)M_sL \quad 3.1$$

Where V_R = the design daily substrate-water mixture loading volume (m^3/day)

R_s = substrate proportion in mixture

R_w = water proportion in mixture

M_s = design mass of fresh substrate to be loaded daily (kg/day)

L = 1 Litre of water (assuming 1 kg of substrate was equal to 1 litre of water)

This gave a total daily substrate-water mixture loading volume of about 20 L or $0.02m^3$.

3.3.2 Construction of the trenches and assembly of the polyethylene tubes

Marti-Herrero's methodology (2012) was used to calculate the optimum dimensions for the trench considering the tube roll circumference (C_m) of 1.2 m. The determined optimum dimensions were, 0.23m for the lower width of the trench (a), 0.31m for the upper width of the trench (b) and 0.29m for the depth (p). The trench was 3.98m long

and had a cross section area of 0.08m^2 . Excavation and construction of the trenches, assembly of the polyethylene tubes and their installation were done according to Luer (2010) methodology. Each digester system was made up of a double layer of tough clear polyethylene tubes with a thickness of 100 microns and measuring 0.38 m in diameter and 4 m in length. The tube was sealed at both ends with 75 mm (3") PVC pipes which acted as inlets and outlets for waste feed materials. Fig. 4 is a picture of completed trenches whereas Fig. 5 is a picture of a completed assembly of polyethylene tubes hanged to the roof.



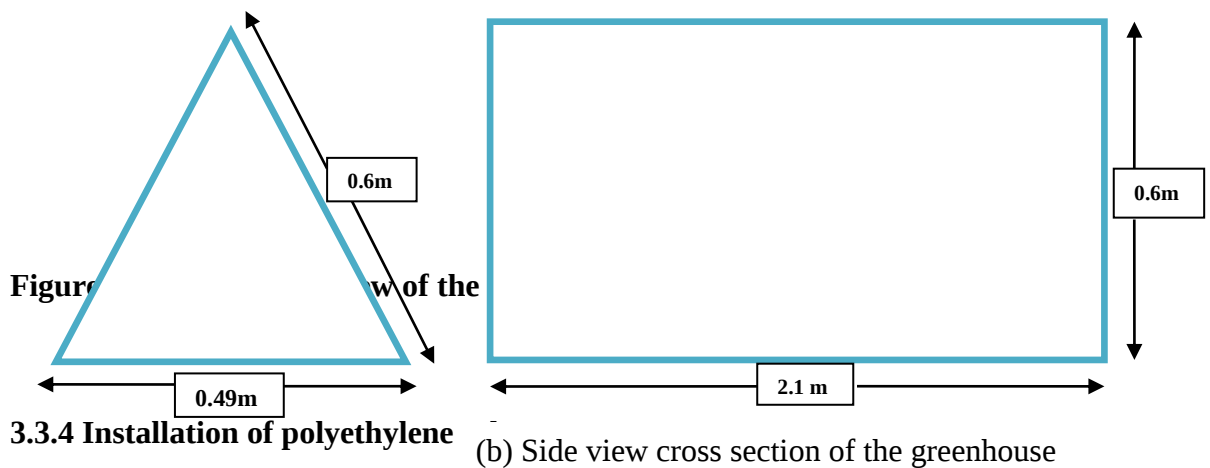
Figure 4: Completed trenches inside a bamboo enclosure at the project site



Figure 5: Assembled polyethylene tubes hanged to the roof for safe keeping before installation

3.3.3 Construction of the greenhouses

Three greenhouses were constructed, one for each of the three pairs of digesters. A complete greenhouse for each digester was a combination two separate greenhouse units of about 2.1 m in length each. A greenhouse unit was made up of frames of soft wood joined in such a way as to form a three dimension triangular structure which was then covered with a sheet of clear polyethylene material. The base of one end of the unit was left open to create room for inflation of digester when installed. It was on these ends that the two greenhouse units were connected by overwrapping and sealing the plastic covering materials over them.



3.3.4 Installation of polyethylene

(a) Cross section of the front view of the greenhouse

(b) Side view cross section of the greenhouse

The tubes were carefully loosened from the hangers and carried to the trench site with minimal folding. The tubes were then properly positioned in the trenches with the side with gas outlet connection point facing upwards and potential areas of wrinkle formation straightened out. A 12.7 mm ($\frac{1}{2}$ ") PVC gas outlet pipe was then connected to the tube through connection point as shown in Fig. 7. The length of the gas outlet pipe varied from digester to digester but it was about 1 m on average including the elbow connection pipe. On the upper end of the pipe was connected a ball valve. After the ball valve, a bend was created by connecting two pieces of pipes through an elbow adapter. The pipe was supported with a string attached to the roof. After connection of the gas outlet was complete, the ball valve was closed and further pipe extension connection was paused pending charging of the digesters.

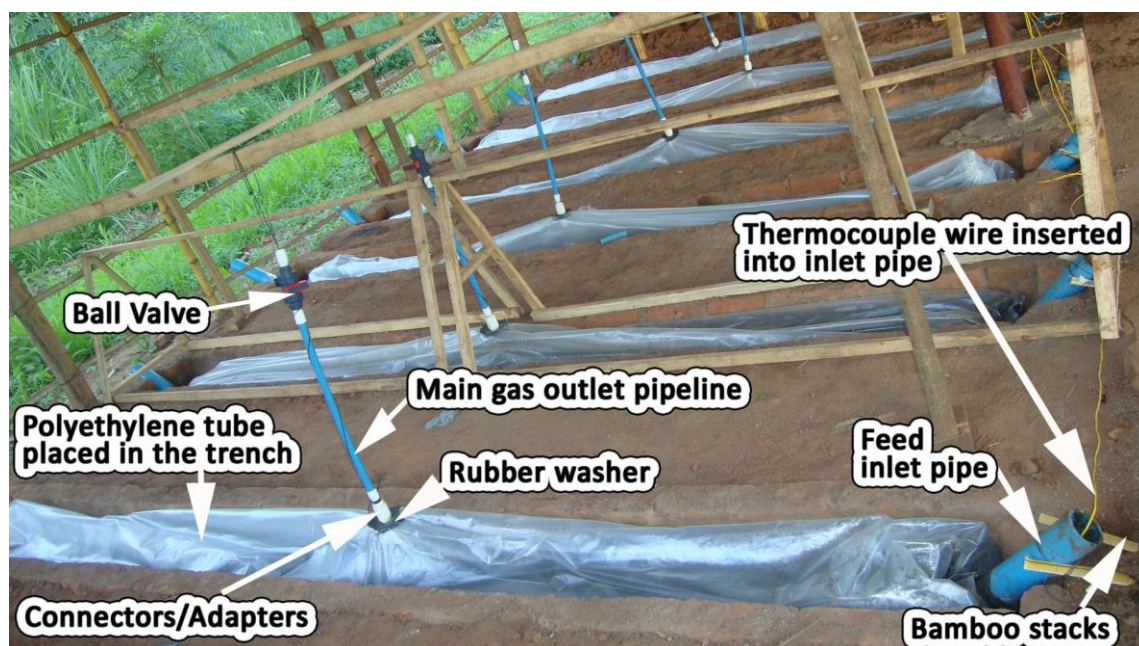


Figure 7: Installation of the tubes into the trenches

3.3.5 Charging of the digesters

Prior to the day of charging the digesters, the test feed materials were mobilised to the study site using a motor vehicle, bicycle and on shoulder where necessary. The materials comprised of one hundred and sixty kilograms (160 kg) each of pig dung, fresh goat stomach contents and food left overs. The pig dung was collected from a piggery farmer at the nearby village of Thom Allan. Fresh goat stomach contents were collected from goat slaughtering sites at the trading centres of Jokala and Matawale, whereas food left overs were obtained from St Marys Secondary school in Zomba district. About 60 kg of cow dung was also collected from a cattle farmer at three miles in Zomba district and were used as an inoculant. The gathered feed materials were pre-treated by beating into smaller particles using bamboo poles and shovels. This was done to facilitate mixing with water. For each digester, 80 kilogrammes of the respective test feed material type was weighed and mixed with 240 litres of water to produce a total volume of 320 litres and a feed material-water mixing ratio of 1:3.

The mixture was then stirred to form a fluent homogenous mixture. Due to limited capacity of the mixing chambers, the exercise was done in phases for each digester. Impurities such as sharp objects, stones, bones, plastic papers and pieces of nylon ropes (found in goat stomach wastes) were also manually removed in the course of the stirring process. Once the materials were well mixed, buckets were used to pour the mixtures into the installed polyethylene tubes through the designated inlet pipes. A short piece of the tubular polyethylene material was cut and tied to the mouth of the inlet pipes to act as a funnel.

3.4 DATA COLLECTION

This section provides details on how the data on the targeted variables was collected. The target variables included amount and quality of produced biogas, ambient temperature, temperature inside the digesters and the greenhouses, pH inside the digesters and the pressure of the gas in the system. Standard equipment for measuring amount of gas produced and gas pressure in the system were not available locally and apparatus were designed for this. It was also important that such apparatus be able to be constructed using locally available materials as the biogas digester system is meant for rural households.

3.4.1 Quantity of biogas produced per day

The amount of biogas produced per day was collected and measured using a displacement system adapted from San Thy and Preston (2003). It comprised of an empty 5- litre cooking oil plastic bottle inverted in 13 litre bucket filled with water. The base of the bottle was open and the mouth was sealed with a stop cork and gum and fitted with small gas inlet and outlet pipes (refer Fig. 8). The height of the

inverted bottle was graduated in into five (5) equal marks each equivalent to a liquid volume one (1) litre. Wire frames were made to anchor and support straight, up and down movement of the 5 litre bottle. The system was designed to operate under pressure generated from the volume of biogas produced. The gas from the digester was directed into the inverted 5-litre bottle which was floated in the larger 13-litre plastic bucket filled with water. With increase in amount of gas being produced, the gas pressure inside the inserted bottles was expected to increase and displace some of the water inside the bottles. However since the system was made in such a way that the pressure required to push the inserted bottle upwards was less than the pressure required to displace the water from the plastic bucket, the increase in pressure inside eventually translated into upward movement of the inserted bottle from its initial position.

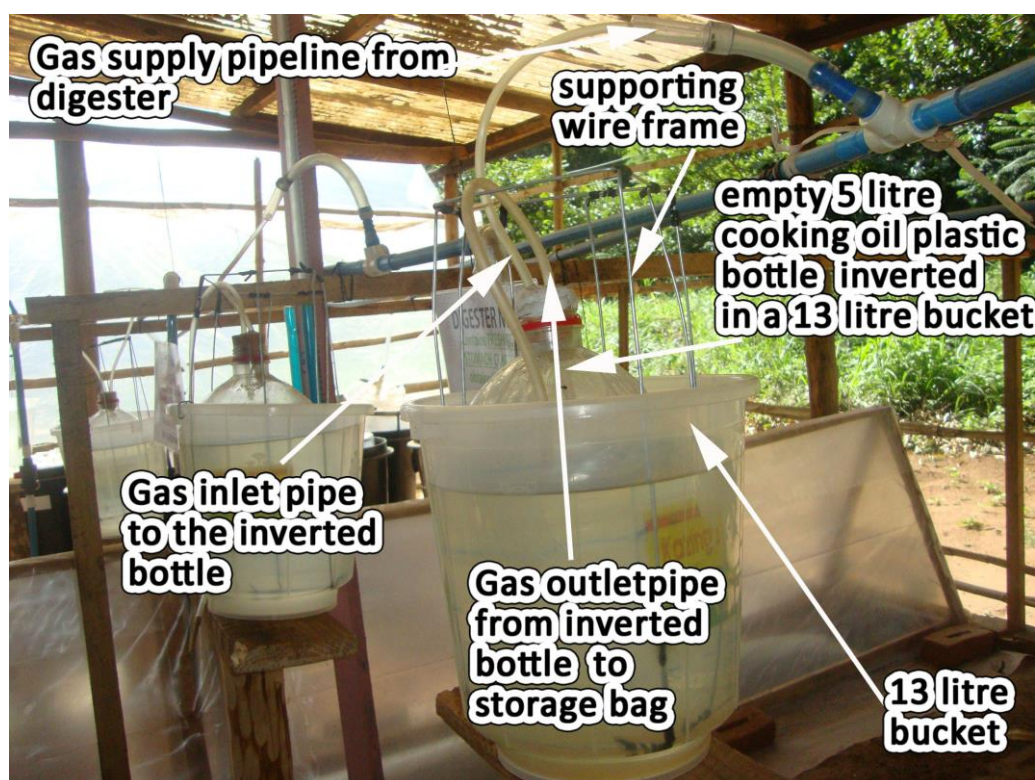


Figure 8: The displacement apparatus used to measure amount of biogas produced

To increase the pressure required to push the inverted bottle upwards, a 16 kg flat piece of wood was wrapped in polyethylene sheet and placed on top of the inflated digesters during gas production measurements. The mass was left resting on the digester while the main gas outlet valve was opened to allow the gas to flow to the measurement device where it caused the inverted bottle to rise to maximum graduated mark in litres. The main gas outlet valve was then closed and the inlet pipe to the inverted bottle was also blocked by folding. The outlet pipe on the inverted bottle was then opened to allow the gas to flow to the gas storage bag that was hanged above the apparatus. As the gas was released to the gas storage bag, the inverted bottle went down to rest at its initial position. The valve to the storage bag was then closed. This cycle of events was repeated until the inflated digester became flattened. The number of times the inverted bottle was completely filled was counted and multiplied by the marked maximum reading to obtain the total amount of gas produced in litres for the 24 hour interval. This was done for each digester every morning at eight o'clock for a period of 30 days. Data was collected for a period of one month starting from the 6th of May, 2013 to the 6th of June, 2013.

3.4.2 Methane Content

The Dräger (Dräger Safety AG & Co. KGaA, X-am 7000 model) gas monitor was used to assess the content of methane in the biogas that was produced in the experiment. The device had an electronic sensor for methane detection and concentration estimation. The biogas was sampled using polyethylene bags made from the same clear polyethylene material used to make the digester (see Fig. 9).



Figure 9: The device used for measuring content of methane placed inside a sampling bag

3.4.3 Gas pressure

An attempt was made to measure the pressure of the gas that was produced in the system using a hand crafted manometer due to local unavailability of standard equipment compatible with the corrosive nature of biogas. The system was adapted from Almoustapha et al., (2009). A total of six U-tube manometers were crafted, one for each digester. When main gas outlet ball valve was opened, the gas was expected to flow to the U-tube manometer through the connected arm and cause the level of water in the left column to drop while that on the right column to increase. The change in height was then to be recorded and used to estimate the pressure in centimetres of water column (see Fig. 10). It was however discovered that the

pressure generated by the system was too low to operate the manometers hence no data was eventually collected.



Figure 10: U-tube manometers connected to gas outlet pipe line

3.4.4 Temperature

Temperature data was collected in three categories. There was collection of temperature data inside each of the digesters. This was done using six K-chrome thermocouple wire probes that were inserted into each of the digesters and connected to a CR10 automatic data logger. The CR10 automatic data logger was powered by a 12v battery which was charged by a solar panel. The data logger was programmed using PC200W 4.1 software which is data logger software for many data loggers manufactured by Campbell Scientific Inc. The data logger system was tested to check and evaluate that it was working before it was set to continuously compute and store hourly average and standard deviation data of the temperature readings from the thermocouple wires. The data was then periodically downloaded into an excel sheet using a computer. Data on the temperature inside the digesters was collected for a period of two months.

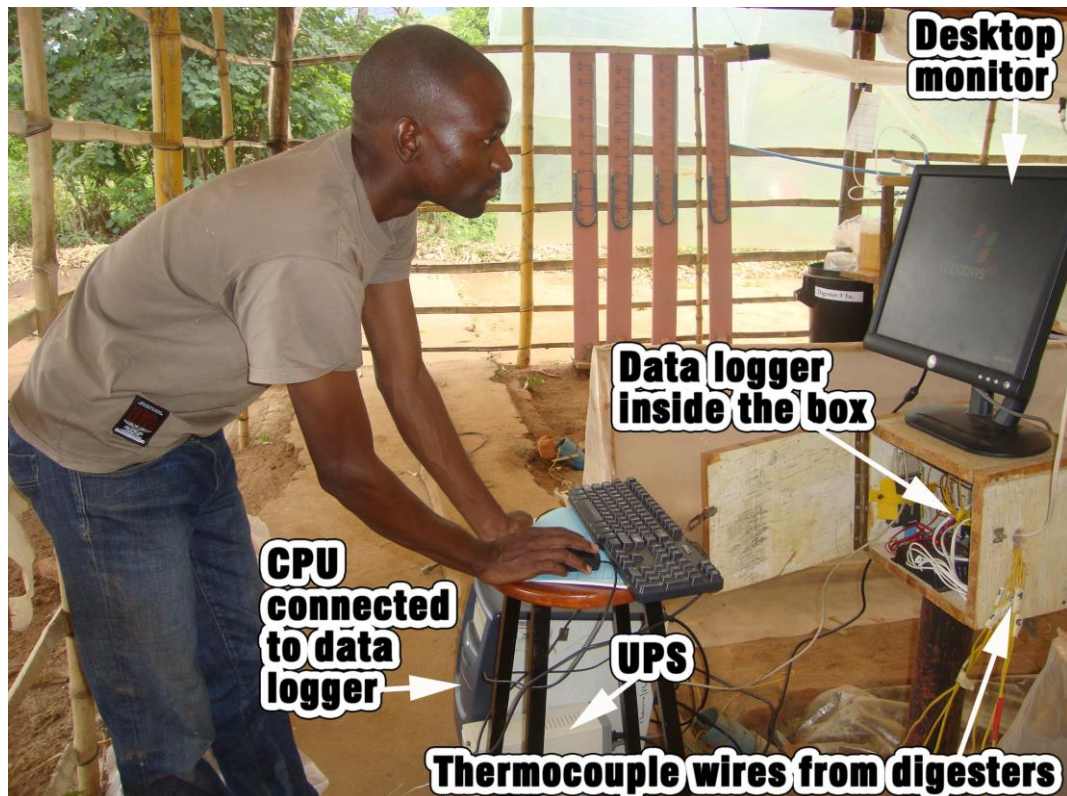


Figure 11: Internal digester temperature data download in progress

Data was also collected on the temperature inside the green houses. This was done using a hand held digital temperature multi-meter (Brymen, TBM815 model) with a thermocouple wire probe extension. The probe was inserted into the green house and then the switching knob of the machine was adjusted to the correct position for taking temperature readings in degrees. Data was collected at an hourly interval both day and night for a period of one month. The personnel providing security at the project site were trained on how to operate the machine and then engaged to assist in collecting data during the day and at night. The data was recorded on specially designed data recording forms.

Lastly, data was also collected on ambient temperature of the project site. This was done at the same time and almost in the same way as the collection of data on the temperature inside the green houses. The only difference was that, to take the ambient

temperature readings, the end of the wire probe was suspended in the air at a central point of the project site.

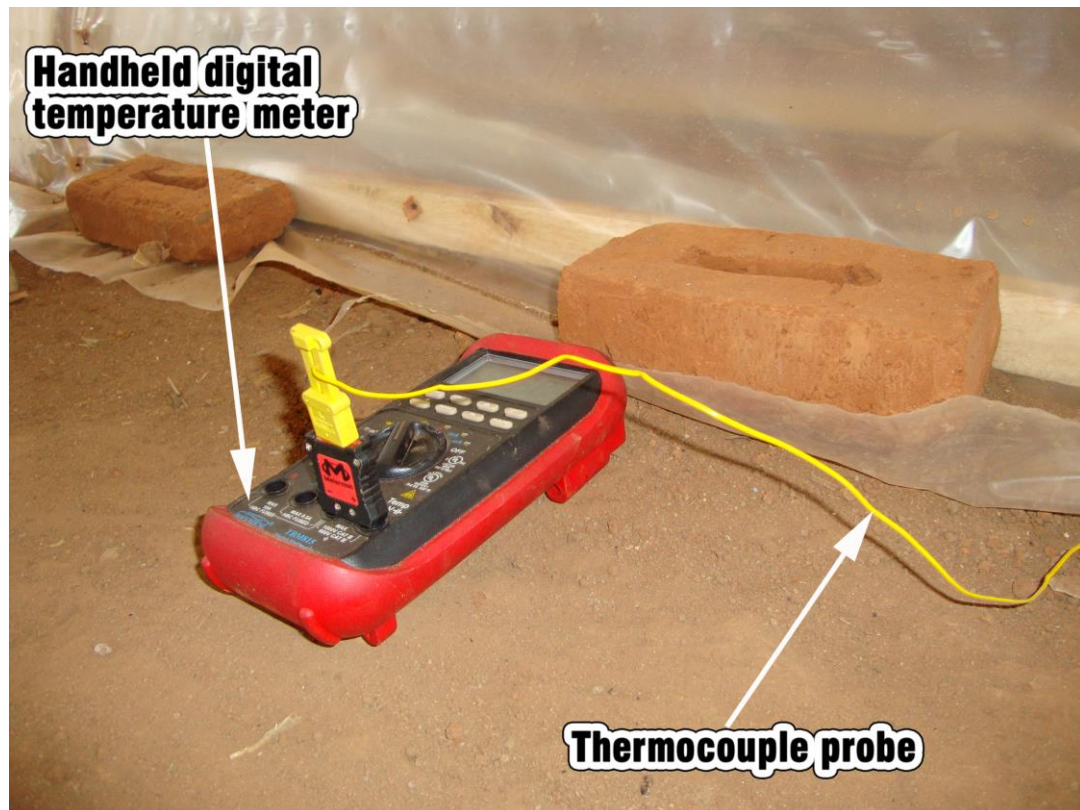


Figure 12: Digital temperature meter that was used to measure ambient and greenhouse temperature

3.4.5 pH

Samples for pH analysis were siphoned from inside the digesters using a 2 m long 12.7 mm (½") PVC pipe which was inserted from the end of the effluent outlet pipe. A different sampling pipe was used for each of the six digesters. During each sampling schedule, one sample was collected per digester giving a total of six samples. The measurement was done twelve (12) times in the course of the experiment and it was done onsite using the field pH meter (Oakton, Eco-Testr pH2 model) and/or in the laboratory using a bench based digital pH meter (Metrohm, 827 pH Lab Model) as recommended by APHA (1999).

3.4.6 Flammability test

An additional test was carried out to see whether the produced gas was flammable and the quality of the flame if found to be flammable. To achieve this, a temporary gas lighter/burner was improvised by attaching a 1 m, 12.7 mm ($\frac{1}{2}$ ") metal pipe to the end of a PVC pipe connected to a gas storage bag. Gas flow from the storage bag to the burner pipe was controlled by loosening or tightening rubber strap that was tied beneath bag-pipe connection point. Data on the quality of the flame was collected through simple visual observations backed by colour photographs.

3.5. DATA ANALYSIS

Microsoft Excel was used to capture and store the data and also carry out minor analysis and presentation. Most of the Analysis and presentation however was done using the statistical package for Social Scientists (SPSS) software. Gas production data was analysed using independent samples t-test to see whether there was significant difference in the mean daily biogas production quantity between the pig dung and goat stomach wastes and also between digesters operated under the green houses and the open. The same was also used to analyse equality of means of methane composition data across the feed types. Temperature data was analysed in SPSS using factorial ANOVA to see whether there was significant difference in internal temperature of digesters fed with the three different feed types and operated in the open and greenhouse. SPSS was also used to analyse the pH data to estimate the mean. Data on pressure was not collected because the pressure of the produced gas was too small for the designed u-tube manometers.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the results of the study. The results presented here include comparison of gas production and the quality of the gas among the feed types and the different digester operation environments. Secondly, results of the temperature inside and outside the digesters are also presented. Lastly, the results of pH of the feed material inside the digesters and flammability of the produced biogas are presented.

4.1 GAS GENERATION ONSET

In general, digester inflation as a sign of gas generation first appeared in digesters containing pig dung within a day, and this was followed by digesters containing goat stomach wastes (after 3-4 days). Though a specific reason for quick onset of gas production in pig dung digesters may be a subject for further research, immediate gas production from pig manure was also reported by Ferrer et al., (2008). One of the possible explanations can be the fact that despite using the same type and quantity of inoculum, the growth and composition of microorganism populations would vary from feed type to feed type depending, among other things, on the ease of adaptability to the feed type (Al Seadi et al., 2008). It generally appears therefore that in this case, the microbial population may have had less challenges to adapt to pig dung feed type compared to the other feed materials. The 3-4 day lag time in goat stomach

wastes digesters may have been due to longer stabilisation of the microbial population in the digesters containing this feed type.

On the other hand, it took two weeks for the digesters containing kitchen food wastes to start showing some inflation as a sign of gas production. The inflation was however short-lived thereby preventing collection of meaningful gas production data. For this reason, these digesters were not included in the gas production quantity analysis. However the methane content of the little amount of the gas that was collected was analysed. The main possible contributing factor to longer lag time and minimal gas production in kitchen food wastes digesters appears to have been the low pH that was observed and is discussed in detail in section 4.4. According to Xie (2012), low pH values are not conducive to the biogas production process. Table 1 gives the details of the time taken for each digester to start showing signs of gas generation.

Table 1: Time (days) taken by each feed type digester arrangement to start showing signs of gas production

Digester Type (feed type and operation environment)		Period taken to start getting inflated (Days)
1.	Pig dung _Open	1
2.	Pig dung _Greenhouse	1
3.	Goat Stomach wastes_ Open	4
4.	Goat Stomach wastes_ Green House	3
5.	Kitchen food wastes _Open	2 weeks, then digestion stopped
6.	Kitchen food wastes _Green House	2 weeks, then digestion stopped

4.2 BIOGAS PRODUCTION QUANTITY

Table 2: Summary of amount of biogas production per feed type and operation environment

Digester operation environment	Biogas production according to type of feed material in litres					
	Pig dung			Goat stomach wastes		
	Mean	SE	C.I. (95%)	Mean	SE	C.I. (95%)
Open	32.8	1.80	32.8 ± 3.5	37.3	1.8	37.3 ± 3.5
Greenhouse	32.3	1.79	32.3 ± 3.5	40.6	2.5	40.6 ± 4.9
OVERALL	32.6	1.26	32.6 ± 2.5	39.0	1.5	39.0 ± 3.0
Biogas production according to type of digester operation environment in litres						
OVERALL	Open			Greenhouse		
	Mean	SE	C.I. (95%)	Mean	SE	C.I. (95%)
	35.1	1.4	35.1 ± 2.8	36.4	1.4	36.4 ± 2.8

Table 2 gives the quantities of the gas produced from the pig dung and goat stomach wastes. In general, it can be noted from Table 2 that biogas production from the digesters operated on goat stomach wastes was 39.0 L/day, ($SE = 1.5$) while from digesters containing pig dung was 32.6 L/day, ($SE = 1.3$). The difference was significant based on the T-test carried out that gave $t(118) = -3.221$, $p < 0.05$ where SE is the standard error, $t(X)$ is value of the t-statistic with X degrees of freedom while p is the probability of obtaining the t-statistic on a t-distribution at X degrees of freedom. These results are in agreement with theoretical values in literature in which biogas production from animal intestine contents is generally estimated to be higher than from pig manure (Al Seadi et al., 2008). Higher quantities of biogas were realised from goat stomach wastes possibly due to higher content of fresh partially digested organic substances and materials which allowed prolonged action of anaerobic bacteria compared to pig dung which was a relatively complete digested material. According to an anaerobic digestion web page, yield from a particular feed stock will among other things vary according to energy left in the feed stock. If the

feed stock has undergone prolonged storage, it may already have begun to breakdown (www.biogas-info.co.uk/biogas-yields.html).

With regard to the environment under which a digester was operated in general, average biogas production from digesters operated under greenhouse was 36.4 L/day (SE= 1.4) while in digesters operated in the open, production was 35.1 L/day (SE = 1.4), as indicated in Table 2. The difference was not significant based on the T-test which gave $t(118) = -1.367$, $p > 0.05$. This suggests that the environment under which a digester was operated had no significant effect on the amount of gas produced. This can possibly be explained by the observed insignificant differences between the temperature inside the digesters under greenhouse and those in the open (see section 4.4). This is because higher temperatures are critical for increased anaerobic methanogenic bacterial activities (Karki, et al., 2005). Pham et al., 2014 also did not find significant difference in biogas production between insulated and uninsulated digesters with a temperature difference of ~ 1 °C. Fig. 13 is a comparative bar graph display of the average amount of gas production and standard error bars according to feed type and the environment under which the digesters were operated.

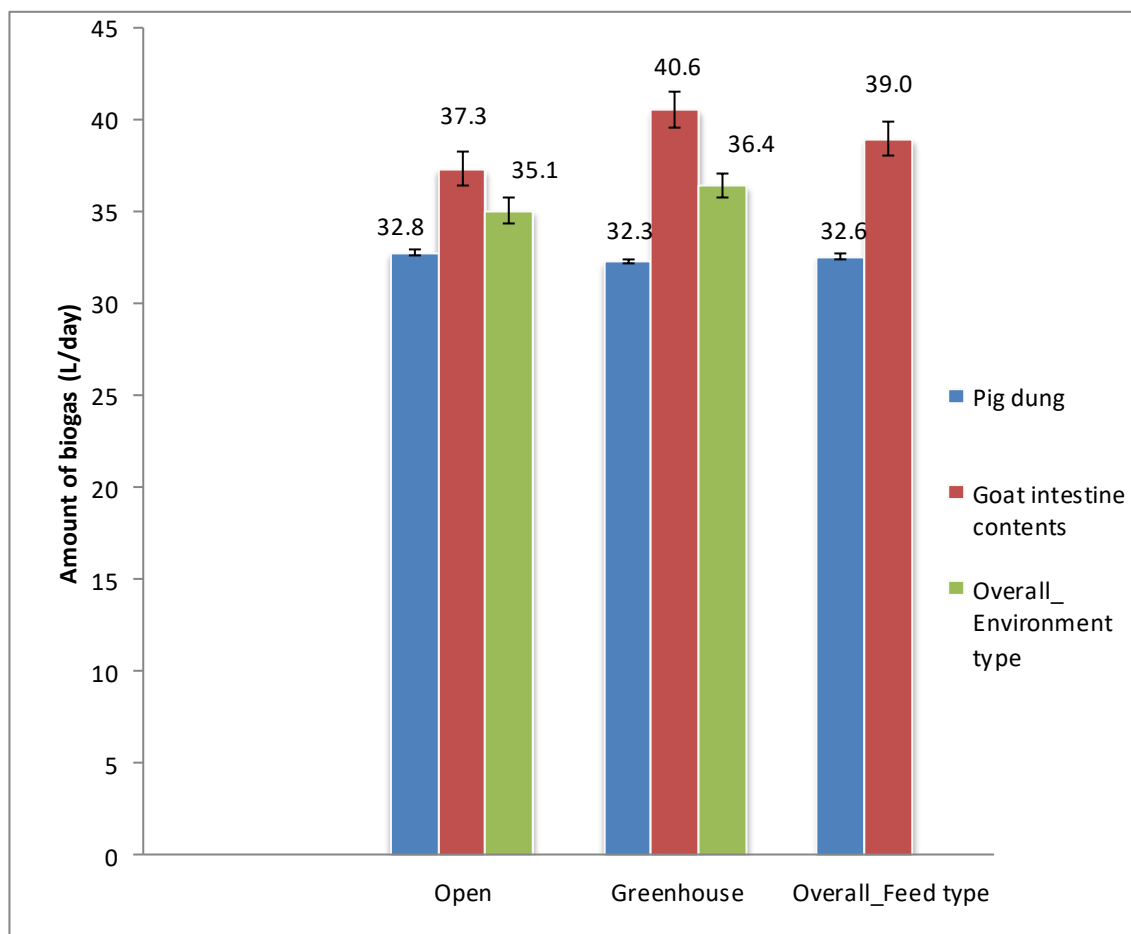


Figure 13: Mean biogas production rates according to feed type and digester operation environment.

Figure 14 is a plot of amount biogas produced per day from each of the digesters for a period of 30 days. In general, it may be observed from the graph that from the 1st to the 19th day, there was a large variation in quantity of biogas produced between consecutive days as well as between the environment and feed types. However between the 20th and 30th day, amount of gas production became less variable between the environment and feed types and from one day to the next. This can be explained in terms of increased stability of physical and biochemical conditions and processes

inside the digesters with time thereby enabling more stable anaerobic methanogenic activities (Schnurer and Jarvis, 2009).

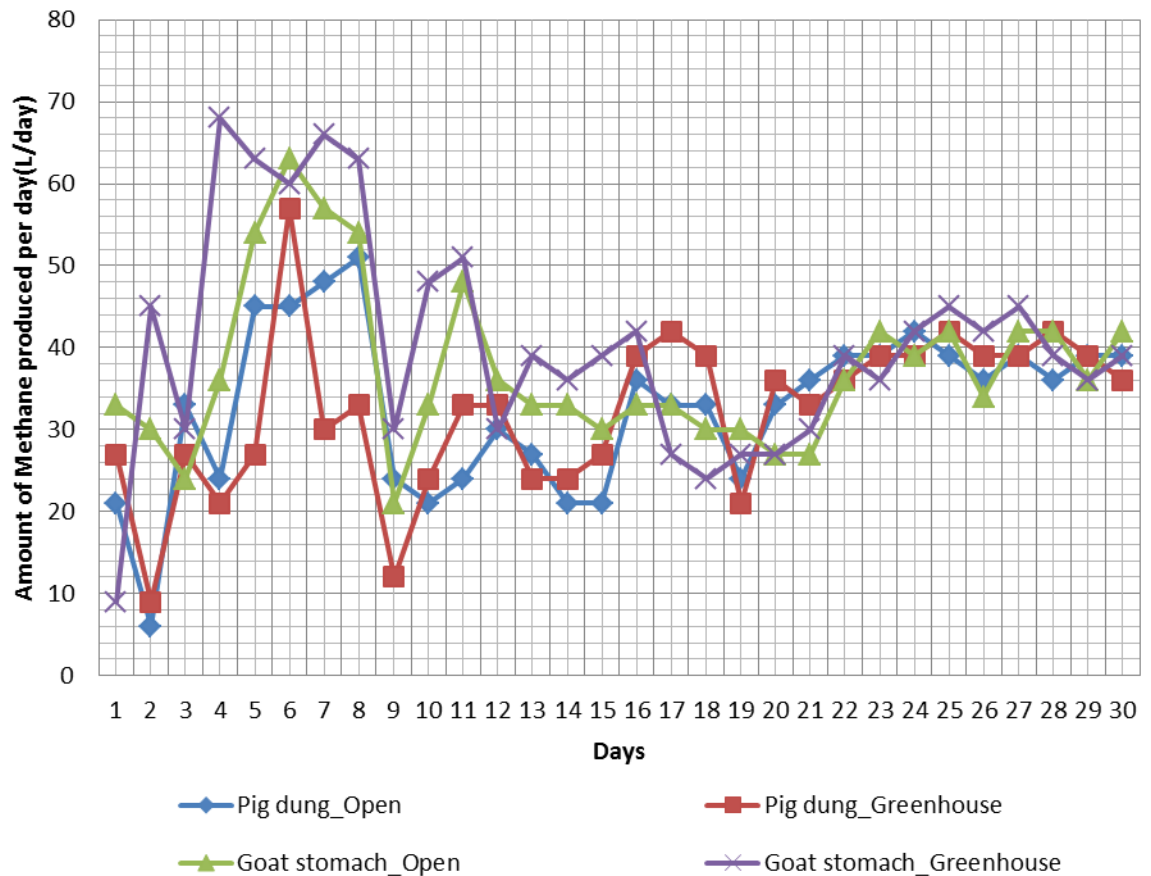


Figure 14: Biogas generation trends according to feed type and digester operation environment.

4.3 METHANE CONTENT

On average, biogas from a digester containing goat stomach wastes had 67.3 % methane while that from pig dung contained 57.0 % methane. This difference can among other things be attributed to the inherent differences in the physical and chemical characteristics of the two feed types. Dublein and Steinhauser, (2008) suggests that composition of the substrates can influence content in the biogas when he states that addition of long-chain hydrocarbon compounds such as materials that

are rich in fats can improve quality of methane i.e. increase content of methane provided that quantities are not too large to avoid acidity.

On the other hand, percentage of methane in the biogas from digesters containing pig dung that were operated in the open and under greenhouse was found to be 56.4 % and 57.5% respectively. Similarly, for digesters containing goat stomach wastes and operated in the open and under a greenhouse, the percentage of methane was 67.2% and 67.5% respectively. It may be observed that the differences in the content of methane between the biogas from open and greenhouse digesters was minimal suggesting that the greenhouse environment may have had little effect on the content. On the other hand, the gas collected from the greenhouse digester containing kitchen food wastes had a lowest methane content of 31.1% indicating the inefficiency of the methanogenic processes which eventually came to a halt. In general, the values of methane content obtained in the study are much higher compared to other studies done at similar ambient temperatures (Ferrer et al., 2008). This may be due to differences in the digester design and also the power of the inoculum that was used as it has been suggested to have an impact on the composition of the biogas (Hobson and Shaw, 1973). Fig. 15 is a bar graph showing the percentage content of methane in the biogas from the study.

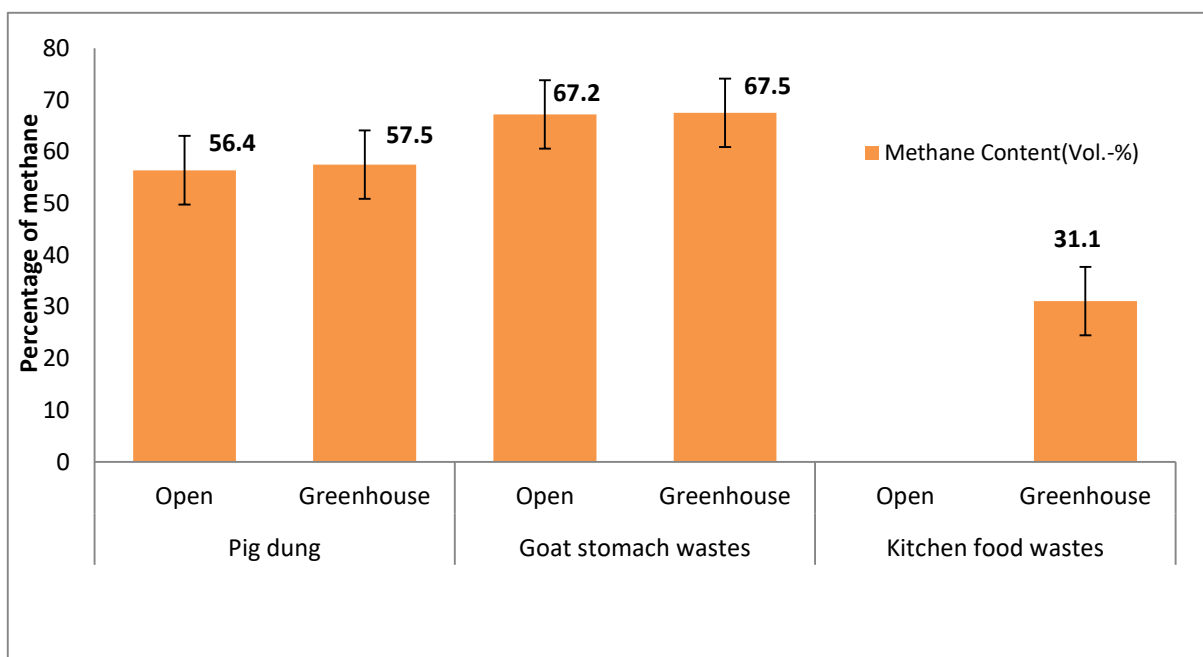


Figure15: Bar graph showing average methane content of biogas (Vol.-%) for the feed types and digester operation environment

4.4 TEMPERATURE BEHAVIOUR

Table 3: Mean temperature inside the digesters according to type of feed material and environment under which it was operated

3. Type of feed material used in a digester * Environment under which digester was operated						
Dependent Variable : Hourly mean temperature inside a digester						
Type of feed material used in a digester	Environment under which digester was operated	Mean temperature inside the digester(C°)	Standard Deviation	Std. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
Pig Dung	Open	23.8	0.6	0.2	23.4	24.3
	Greenhouse	24.0	1.7	0.2	23.6	24.4
	Overall	23.9	1.3	0.2	23.6	24.2
Goat Stomach Wastes	Open	22.5	1.5	0.2	22.5	22.9
	Greenhouse	23.0	1.0	0.2	22.6	23.5
	Overall	22.8	1.3	0.2	22.4	23.1
Kitchen food wastes	Open	23.1	0.6	0.2	22.7	23.6
	Greenhouse	23.6	0.4	0.2	23.2	24.0
	Overall	23.4	0.6	0.2	23.1	23.7
	Greenhouse	23.5	1.2	0.1	23.3	23.8

As may be noted from Table 3, the average hourly temperature inside digesters ranged between 22.5 °C (goat stomach wastes digester in the open) and 24.0 °C (pig dung digester in a greenhouse) with standard deviation ranging from 0.4 °C to 1.7 °C. These temperatures appear to fall on the lower end of the mesophilic temperature range for anaerobic digestion (Al Seadi et al., 2008; Dublein and Steinhauser, 2008). The fact that the experiment was conducted during cooler months of the year may have contributed to this development (Zomba District Assembly, 2009). Kalia and Kanwar, (1998) noted that simple biogas digesters without heating and stirring are influenced significantly by season, especially in cold winter climates. This implies that in warmer months or areas of the country, higher quantities of gas production rates could be obtained from this digester technology since higher temperatures are critical for increased methanogenic activity (Karki, 2005). ANOVA results for the hourly mean internal digester temperature with respect to feed type and environment are summarized in Table 4.

Table 4: Results of Univariate Analysis of Variance of the hourly mean internal digester temperature with respect to feed type and environment

Tests of Between-Subjects Effects						
Dependent Variable: Hourly mean temperature inside a digester						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	38.15369	5	7.631	6.457	0.000	0.1896
Intercept	78458.52	1	78458.521	66386.571	0.000	0.9979
Feed type	31.96131	2	15.981	13.522	0.000	0.1639
Environment type	5.377968	1	5.378	4.550	0.035	0.0319
Feed type * Environment type	0.814417	2	0.407	0.345	0.709	0.0050
Error	163.0944	138	1.182			
Total	78659.77	144				
Corrected Total	201.2481	143				
a. R Squared = .190 (Adjusted R Squared = .160)						

From the table, it appears that there was a significant main effect of type of feed material on the average hourly temperature with $F(2, 138) = 13.52$, $p < 0.05$, $\omega^2 = 0.08$, as shown in Table 4 where $F(a, b)$ is the calculated value of the F-ratio with a degrees of freedom for the levels of the independent variable and b degrees of freedom for the total number of cases, p is the probability of obtaining the value of the calculated F-ratio at (a, b) degrees of freedom which is compared to a chosen significance level of 0.05 and ω^2 is the measure of the size of the effect of the experimental manipulation (Field, 2005). This is no surprise as different feed types are expected to exhibit different temperature behaviour due to differences in physical and chemical properties (Dublein and Steinhauser, 2008).

In terms of the environment under which the digesters were operated, results of Two-Way Independent ANOVA indicated that there was a significant main effect of environment under which digester was operated on the average internal digester temperature in general, with results of $F(1, 138) = 4.55$, $p < 0.05$, $\omega^2 = 0.01$ (see Table 4). This explains the observation that the mean internal digester temperatures in digesters operated in the open were slightly lower than those operated under greenhouse (see Table 3). The greenhouse environment helped to keep the temperature in the digesters warmer and more stable by allowing incoming sunshine radiation but limiting heat exchange with the external environment (www.hyperphysics.phy-astr.gsu.edu/hbase/thermo/grnhse.html). However it must be noted in this case that the size of the effect was very small ($\omega^2 = 0.01$) which agrees with the small margins of the internal digester temperature differences between the open and greenhouse environments. Similarly, the value of R-squared was .19, meaning that only about 19% of the variation in the temperature between greenhouse

and open digesters could be explained in terms of the type of environment under which the digesters were operated (Field, 2005). This also partly explains the insignificant differences in the amount biogas production and the content of methane in the biogas from digesters operated under the greenhouse and in the open. According to Dublein and Steinhauser, (2008), a temperature difference of $\pm 2\text{ }^{\circ}\text{C}$ is not big enough to affect the anaerobic digestion process drastically. In this study, the average difference in internal temperature between greenhouse and open-operated digesters was $0.4\text{ }^{\circ}\text{C}$ and is well below $2\text{ }^{\circ}\text{C}$.

The small size of the temperature differences may be explained in terms of the design of the digester in which the liquid portion lays in the underground trench surrounded by a thermal mass of dry soil whose temperature is generally less variable (Farouk, 1981; Phillip and Itodo, 2007). Above the liquid portion in the digester was the gaseous phase whose thermal conductivity is also a relatively poor (Lang, 2014). The warming and heat stabilizing effect of the greenhouse was therefore attenuated by these factors leading to relatively small differences in the values of mean internal digester temperatures between open and green house digesters. It may therefore be concluded that under conditions similar to those in the study, inclusion of greenhouses offers little benefit. Lastly, the Two-Way Independent ANOVA also showed that there was no significant interaction effect between the type of feed material and digester operation environment on the average internal digester temperature, with results of $F(2,138) = 0.345$, $p > 0.05$, $\omega^2 = -0.001$ (see Table 4.4). This is important because it gives additional confidence that the observed variation was mainly due to either the feed type or the environment under which the digester was operated and much less by the interaction of these two factors.

With regard to temperature trends inside the digesters, Fig. 16, 17, and 19 give a comparative display of the mean hourly ambient temperature and mean hourly temperature inside the open and greenhouse digesters for each feed type across a 24 hour period.

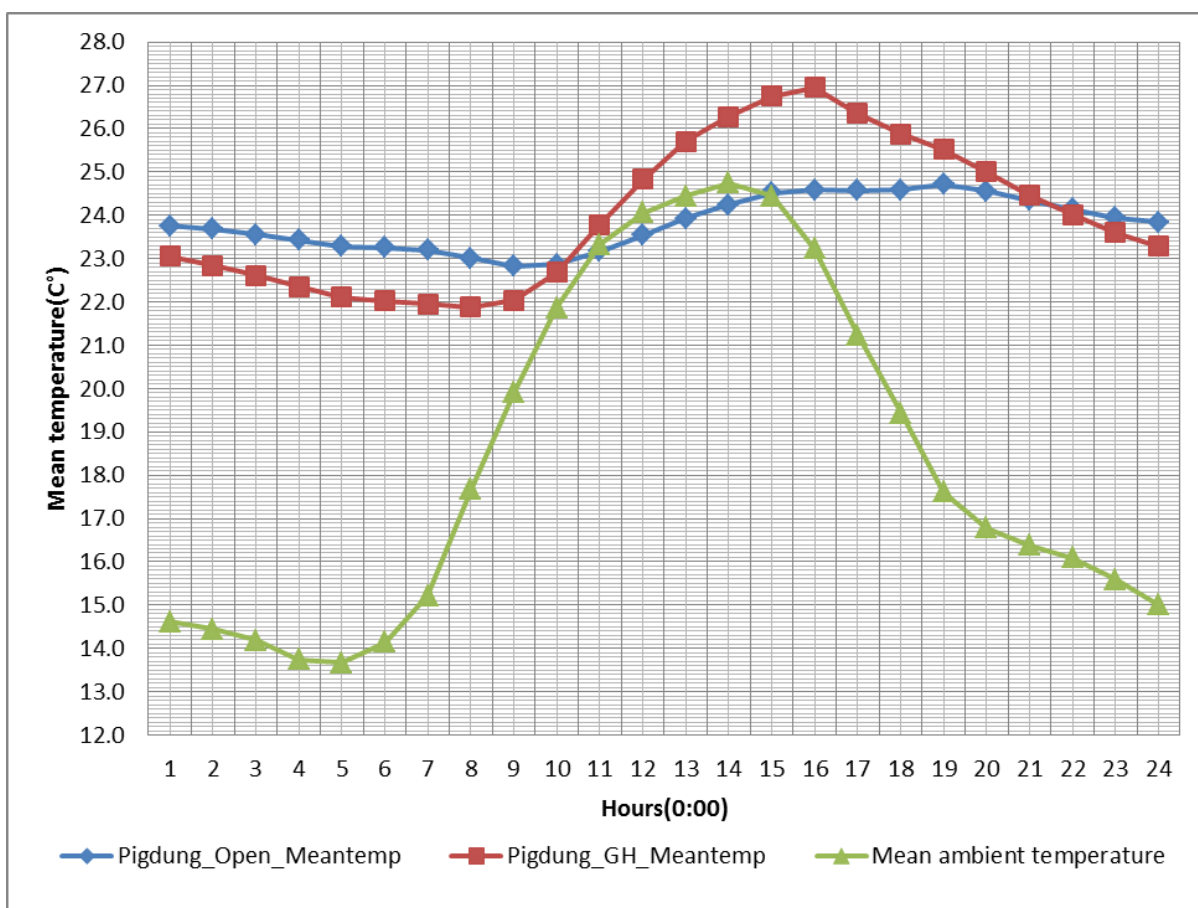


Figure 16: Comparative ambient and hourly mean temperature trends inside and outside pig dung digesters operated inside greenhouse (GH) and without a greenhouse (Open).

It may be observed from Fig. 16 and Fig. 17 that in digesters containing pig dung and goat stomach wastes, the temperatures inside the digesters generally tended to be low during early morning hours from about midnight to 05:00hrs in both open and greenhouse digesters. From about 06:00 hrs the temperature began to rise until it reached its peak between 14:00 hrs and 17:00 hrs after which it also started to drop. In

general, the variation in both cases appears to be in tandem with the progression of the ambient temperature (see Fig. 16 and 17). In other studies it was similarly observed that temperature inside simple unheated digesters followed the trend of ambient air temperature with the result that the maximum(peak) temperature was found a few hours after noon (Pham et al., 2014; Perrigault et al., 2012; Park and Riddle, 2010; Khoiyoungbam et al., 2004).

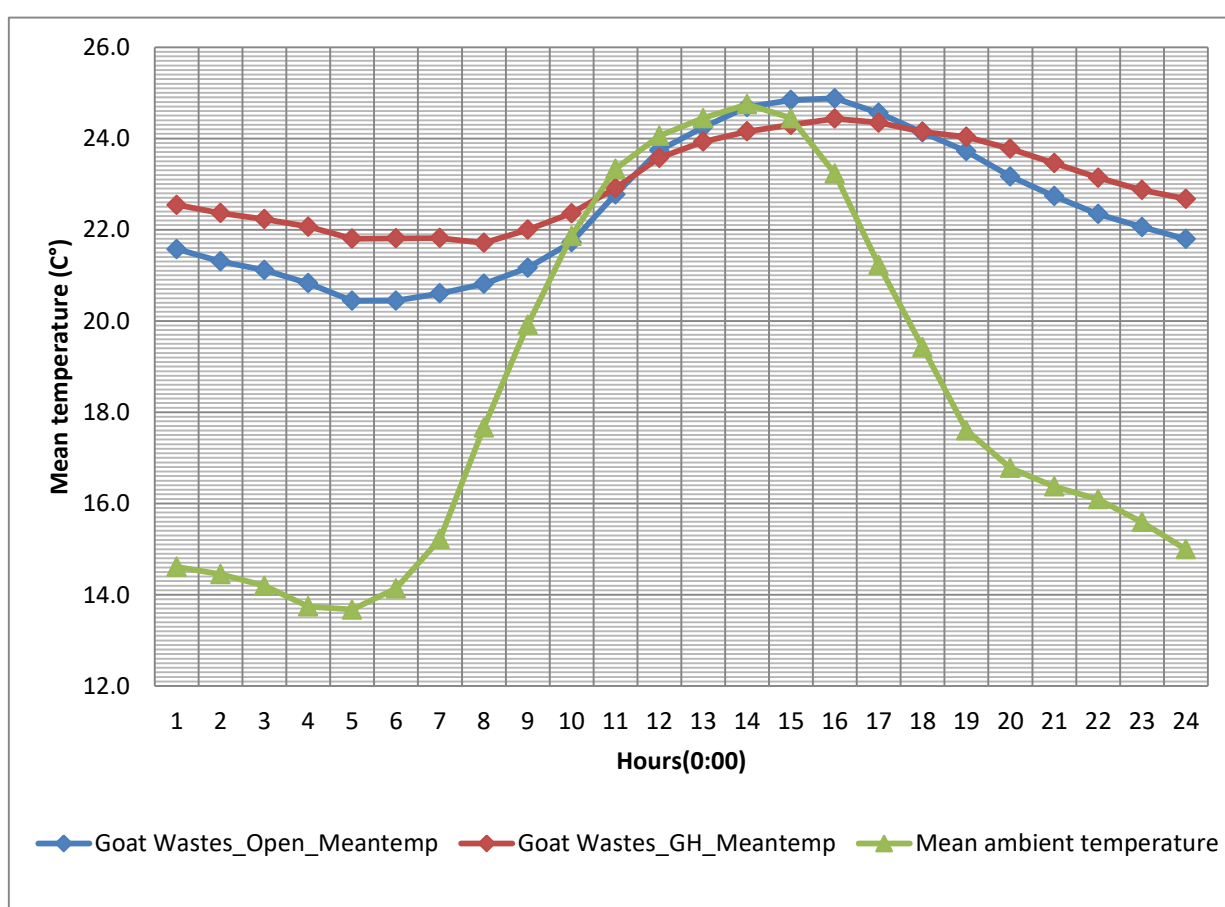


Figure 17: Comparative ambient and hourly mean temperature trends inside digesters containing goat stomach wastes operated under greenhouse (GH) and without greenhouse (Open).

There were also marked differences in the behaviour of temperature inside the digesters between those containing pig dung and goat stomach wastes. For instance, in the digesters containing goat stomach wastes, the temperature inside the greenhouse digester was above that of the open digester during late evening hours to early

morning hours (see Fig. 17) where as in the digesters containing pig dung, the temperature inside the greenhouse digester was below that of the digester in the open during late evening and early morning hours (from about 22:00hrs to 10:00hrs). This is an interesting observation which may require further investigation because according to the greenhouse effect theory (Harrison and Coll, 2007), the temperatures in the digesters containing pig dung were expected to behave more like those in the digesters containing goat stomach wastes. In this study it was additionally noted that the pig dung digesters produced higher peaks than the digesters containing goat stomach wastes. This may have been due to their advantageous positioning at the study site in relation to sun set direction hence got more affected by solar heating (Pham et al.,2014).

In the digesters containing kitchen food wastes on the other hand, temperature trends were markedly different compared to digesters containing pig dung and goat stomach wastes (see Fig. 18). Firstly, the temperatures in the greenhouse and open digesters did not overlap anywhere across the entire 24 hour period. The temperature inside the greenhouse digester remained on top of that of the open digester across the 24 hour duration. Secondly, the temperature in the digesters containing kitchen food wastes was generally relatively higher than that of the pig dung and goat stomach waste digesters during morning hours. The timing of peak and low temperatures was also different in digesters containing kitchen food wastes compared to the pig dung and goat stomach waste digesters (see Fig. 16, 17 and 18). This unique behaviour may be attributed to the minimal microbiological gas production activities in the digesters as the temperature inside a digester is also influenced by the microbial activity on the organic matter (Phillip and Itodo, 2007). As already reported, digesters containing

kitchen food wastes did not show signs of gas production until after two weeks and production ceased again shortly afterwards.

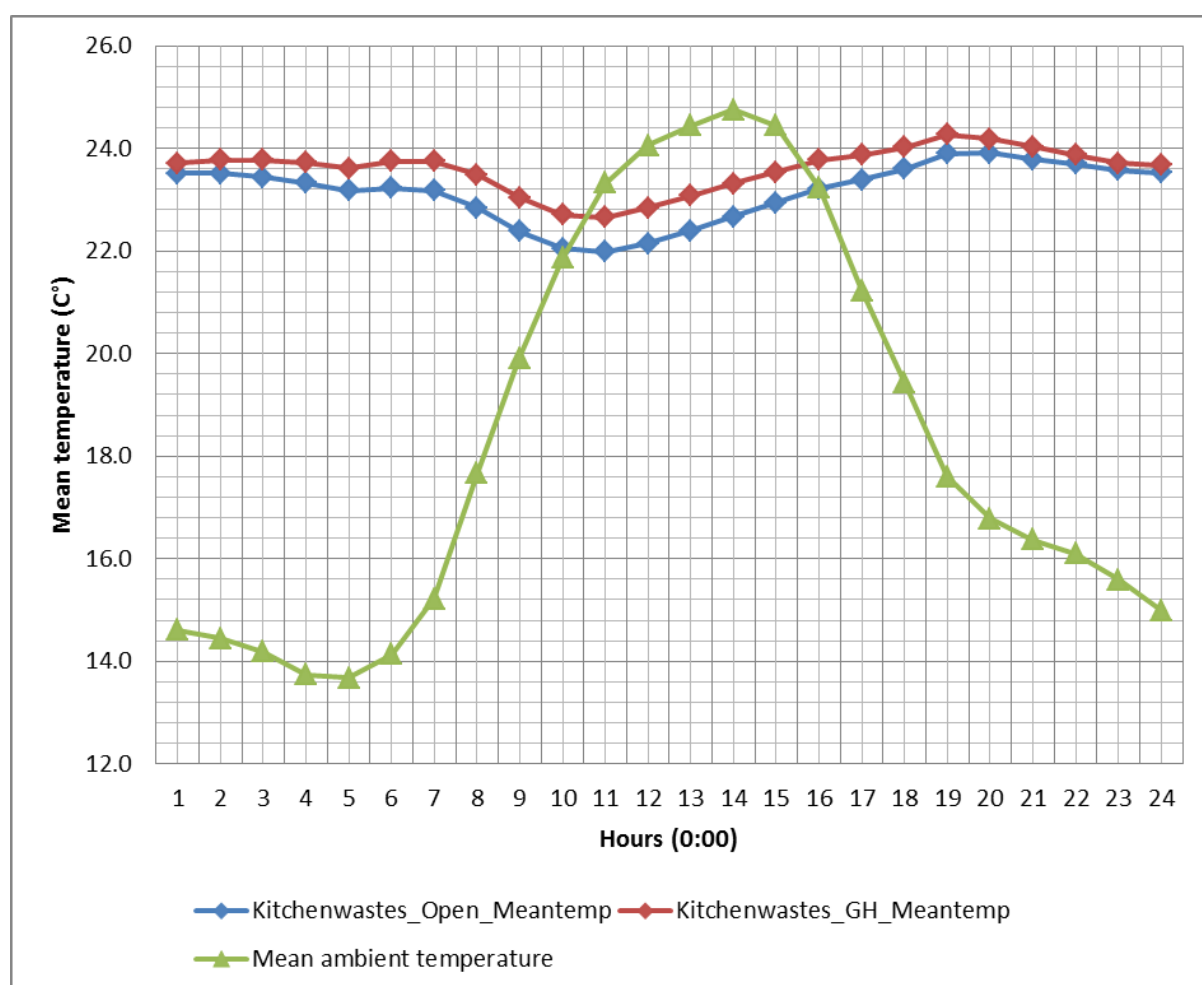


Figure 18: Comparative ambient and hourly mean temperature trends inside digesters containing kitchen food wastes operated in the Open and greenhouse (GH) environment

It may be observed from Fig. 16, 17 and 18 that ambient temperature was generally considerably lower than internal digester temperature during both morning and late evening hours but was almost at par with the internal digester temperatures during peak period of early afternoon hours. Thus, unlike internal digester temperature, ambient temperature varied greatly across the day with a mean of 18.4 °C, standard variation of 4.0 °C, minimum of 13.7 °C and maximum of 24.8 °C. In general, the difference between mean ambient temperatures and mean internal digester

temperatures was about 4.0 °C. This agrees with findings by Perrigault et al., (2012) who also noted that temperatures in the soil and in the digester were higher than those in the ambient air.

4.5. pH INSIDE THE DIGESTERS

Table 5: Mean pH values

Digester feed material type	Environment Type	Mean pH (95% CI)
Pig dung	Open	7.2 ± 0.17
	Green house	7.7 ± 0.16
Goat stomach wastes	Open	6.9 ± 0.07
	Green house	7.1 ± 0.04
Kitchen food wastes	Open	3.9 ± 0.17
	Green house	4.0 ± 0.18

Table 5 shows mean pH values inside the digesters according to operation environment and feed type and it can be observed from the table that pH was lowest in digesters containing kitchen food wastes, 3.9 for open and 4.0 for greenhouse digester. This may have resulted from the predominantly carbohydrate content of the food left overs that were used. The kitchen food wastes were mainly comprised of pieces of *Nsima* (semi solid maize flour porridge). In general, according to Dublein and Steinhauser, (2008), biodegradation of hydrocarbons usually happens without release of pH buffering ions as is the case with proteins. Secondly, degradation of carbohydrates increases the hydrogen partial pressure more easily and this happens in combination with the formation of acidic reduced intermediate products. These factors therefore may have easily caused the pH in the digesters to decrease. Despite efforts to control the acidity by applying lime, the pH still remained low throughout the entire period. This situation may have greatly contributed to inhibition of methanogenic microbial activities as evidenced by delay and failure of the digesters to

sustain exhibited signs of gas production. Most anaerobic bacteria, including methane-forming bacteria, perform well within a pH range of 6.8 to 7.2 (Gerardi, 2003). In another study, Xie (2012) found that a drop in the pH of the system to 5.9 brought methane production to a complete halt. The pH values in pig dung and goat stomach wastes digesters ranged between 6.9 and 7.7. These levels of pH were able to support methanogenic microbial activities hence the observed biogas production from the digesters.

4.6 FLAMMABILITY TEST

Biogas from both pig dung and goat stomach digesters was able to be kindled by a single match stick on a crudely improvised burner suggesting a reasonable content of flammable methane in it. The gas also burned with a characteristic blue flame as shown in Fig.4.8. This agrees with results from biogas methane content analysis in which methane content ranged between 56.4% and 67.7%. Kaisu et al., (2008) found that the flame was sustainable at methane content of between 52 – 56 % and above but quenched at the methane concentrations of less than 45-54 % for carbon dioxide-methane biogas mixtures. This also explains why the gas collected from the digester containing kitchen food wastes did not burn at all.

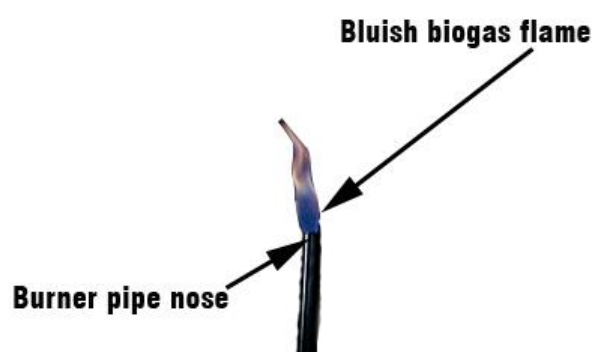


Figure 19: Photograph showing the flame that was produced from burning of the biogas

4.7 PRESSURE

Pressure measurement instruments did not yield any useful data because the pressure from the digesters was too low to operate them under ambient temperature and pressure. It was also for this reason that an additional mass was placed on top of the inflated digesters to increase the pressure and enable daily gas production measurements to take place. Other studies also noted this low or variable pressure behaviour of tubular polyethylene digesters (Rajendran, et al., 2012). The ambient temperatures under which the study was carried out may have enhanced the problem. This low pressure phenomenon is however not entirely a setback as it means that the technology can be safely operated at household level with minimal risk of explosion accidents. However, in some areas this problem had been reduced by hanging some weights on the digesters and gas storage bags (Marti-Herrero, 2011).

CHAPTER 5

CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS

First of all, the study has shown that it is possible to build tubular polyethylene biogas digesters in Malawi using locally available materials. Secondly, the locally constructed tubular polyethylene biogas digesters also performed relatively well even under cooler local weather conditions and feed material types.

In particular digesters containing pig dung were the quickest (1 day) to start producing biogas followed by those containing goat stomach wastes (3-4) days. This implies that for quick digester start up, pig dung is ideal. However the study also revealed that quantity of gas produced each day from digesters using goat stomach wastes was higher (38.95 L/day) than that from digesters containing pig dung (32.55 L/day). In terms of gas quality, it has been shown that goat stomach wastes had higher percentage content of methane (67.3%) than pig dung (56.95%). This means that goat stomach wastes are more preferable than pig dung in as far as gas production quantity and quality is concerned. However considering issues of availability, pig dung is more convenient compared to goat stomach wastes.

Though production of biogas from digesters operated in greenhouses was slightly higher (36.45 L/day) than those in the open (35.07 L/day), the difference was not statistically significant suggesting that inclusion of the green house in the propagation

of the technology may not be worth it in Malawi. Furthermore, the study also revealed that starting up a digester containing kitchen food wastes mainly comprised of remains of *Nsima* (semi solid maize flour porridge) was not easy because they encouraged development of acidic conditions which inhibited biogas generation.

An insight into the behaviour of the temperature inside the digesters with respect to feed material type and environment under which the digesters were operated has also been gained from the study. First of all, it has been shown that the temperature inside the digesters was generally higher than ambient temperature by about 4 °C. Secondly, the study has also shown that the greenhouses had an effect on the mean temperature inside the digesters as they increased the internal digester temperature by about 0.4 °C. The size of this effect was however found to be small ($\omega^2 = 0.01$) thereby corresponding to the minimal difference in daily gas production quantities observed between digesters operated in greenhouses and those in the open. The findings imply that digesters in the open were able to perform almost the same as those in the greenhouses. This has profound cost advantage implications in terms dissemination and adoption of the technology as it means that the technology can be propagated without inclusion of greenhouses thereby maintaining its low cost advantage.

It was also revealed from the study that internal digester temperature generally varied according to progression of sunshine insolation during the hours of the day with temperatures being low during early morning hours and high during late afternoon hours after insolation had reached its peak. This knowledge is important in deciding cost effective ways of including heating devices in case there may be need to improve and optimise the design in the future.

With regard to pH inside digesters, it was found that pH in the digesters containing pig dung and goat stomach wastes was between 6.9 and 7.7 and they worked properly. On the other hand, the pH in the digesters containing kitchen food wastes ranged between 3.9 and 4.0 and these digesters were not able to sustain biogas production. This finding is critical as it may act as a guide in early detection of malfunctions in the digester.

In terms of biogas flammability, the biogas produced from pig dung was found to be just as flammable as that produced from the goat stomach wastes implying that both feed types are able to produce gas of good flammability quality. This implies that, keeping other things constant, those with access to goat stomach wastes can enjoy cooking with biogas as much as those with access to pig dung as a digester feed material. Finally, the study has confirmed that pressure of biogas produced from the tubular polyethylene digesters was very low. Though this may pose a challenge to effective utilisation of the biogas in gas stoves, it can easily be corrected by having a secondary gas storage bag from where gas pressure to the stove may be enhanced by hanging some weights over it. On the other hand the low pressure also means that this digester technology is relatively safe from pressure induced explosion accidents.

Since the present study was just an initial attempt to understand the local feasibility and performance of the technology, it is recommended that further research be continued to deepen the understanding and local optimization of the technology. Possible areas of research may include but not limited to:

1. Testing performance of the digester technology with combinations of more other locally available feed materials to identify the best feed material combinations.
2. Testing the performance of the technology in other climatic regions of the country.
3. Piloting the digesters at household level to assess the social, economic and ecological impact.
4. Innovation of local mechanisms for improving pressure and optimizing temperature in the system.

REFERENCES

- Al Seadi T., Rutz D., Prassl H., Köttner M., Finsterwalder T, Volk S., Janssen R.(2008). *Biogas Handbook*. Esbjerg: University of Southern Denmark.
- Almoustapha O., Kenfack S., and Millogo-Rasolodimby J. (2009). Biogas Production Using Water Hyacinth to meet collective energy needs in a Saherian country. *Field Actions Science. Rep* (2) 27-32. Accessed on 2/27/2009 from: www.field.sci-rep.net.
- American Public Health Association (APHA) (1999). *Standard method for the examination of water and wastewater*. Washington DC: American Public Health Association.
- Bradshaw C.J.A., Sodhi N.S., Peh K.S.H., Brook B.W. (2007). Global Evidence that deforestation amplifies flood risk. *Global Change Biology*, 2379-2395.
- Cortsen L., Lassen M., Nielsen H.K. (1999). *Small Scale Digesters in Turiani Nronga and Amani, Tanzania*. Aarhus-Denmark: University of Aarhus
- Dohhoo C., VanLeeuwen J., Guernsey J.R., Critchley K., and Gibson M. (2013). Impact of biogas digesters on wood utilisation and self- reported back pain for women living on rural Kenyan smallholder dairy farms. *Global Public Health: An international Journal for Resresearch, Policy and Practice*. Accessed on 27/01/2013 from: <http://dx.doi.org/10.1080/17441692.2012.758299>.
- Dublein D., Steinhauser A. (2008). *Biogas from Waste and Renewable Resources-An Introduction*. Weinheim, Germany: Willey VCH GmbH & Co. KGaA.
- Elaiyaraju P., Partha N. (2011). Biogas production from co-digestion of orange peel waste and jatropha de-oiled cake in an anaerobic batch reactor. *African journal of biotechnology*, 11 (14), 3339-3345.

- Farouk O.T. (1981). *Thermal properties of soil*. New Hampshire, U.S.A: United States Army Corps of Engineers.
- Ferrer I., Gamiz M., Almeida M. and Ruiz A. (2008). Pilot project of biogas production from pig manure and urine mixture at ambient temperature in Ventanilla (Lima, Peru). *Waste Management* (article in press). Accessed on 20/12/2012 from: www.elsevier.com/locate/wasman.
- Field A. (2005). *Discovering statistics using SPSS*. London: SAGE Publications Ltd.
- Flavin C. and Aeck M.H. (2010). *Energy for Development: Role of Renewable in Meeting the Millennium Development Goals*. Worldwatch Institute.
- Frost R.J. (2011). *Feasibility of Home Biogas Generation from Food Wastes*. Unpublished Masters thesis, Graduate School of Cornell University, USA.
- Fulford D. (1988). *Running a Biogas Programme: A handbook*. London, UK: Intermediate Technologies Publications.
- Fullerton D.G., Semple S., Kalambo F., Suseno K., Malamba R., Henderson G., Ayres J.G. and Gordon S.B. (2009). Biomass Fuel Use and Indoor Air Pollution In Homes In Malawi. *Occup Environ. Med.*, 66, 777–783.
- Furze J. (2002). *Tubular Plastic Bio-Digesters in Tanzania, Viet Nam, Zimbabwe and China*. Ebeltoft-Denmark: University of Aarhus.
- Garfi M., Ferrer-Marti L., Velo E., and Ferrer I. (2012). Evaluating benefits of low cost household digesters for rural Andean communities. *Renewable and Sustainable Energy Reviews*, 16 (1), 575-581.
- Geraldi M.H. (2003). *The Microbiology of Anaerobic Digesters*. New Jersey, USA: John Wiley & Sons Inc.
- Geraldi M.H. (2006). *Waste Water Bacteria*. New Jersey, USA: John Wiley & Sons Inc.

- Ghani W.A.K., and Idris A. (2009). Preliminary study on production of biogas from municipal solid waste (MSW) leachate. *Journal of Eng. Sci. and Tech.*, 4 (4), 374 – 380.
- Government of Malawi (1994). *National Environmental Action Plan*. Lilongwe: Environmental Affairs Department.
- Government of Malawi (2003). *Report on Malawi's Climate Technology Transfer and Needs Assessment*. Lilongwe: Environmental Affairs Department.
- Government of Malawi (2006). *National Adaptation Programmes of Action*. Lilongwe: Environmental Affairs Department.
- Government of Malawi (2009a). *Malawi Millenium Development Goals Report*. Lilongwe: Ministry of Economic Planning and Development.
- Government of Malawi (2009c). *Malawi Biomass Energy Strategy*. Lilongwe: Department of Energy Affairs.
- Government of Malawi (2009b). *Housing and Household Conditions*. Zomba: National Statistical Office.
- Government of Malawi (2010). *State of Environment and Outlook Report*. Lilongwe: Environmental Affairs department.
- Government of Malawi (2011). *Economic Valuation of Sustainable Natural Resource Use in Malawi*. Lilongwe: Ministry of Finance and Development Planning.
- Government of Malawi (2011). *Terms of Reference for Promotion of Biogas Technology*. Lilongwe: Department of Energy Affairs.
- Gullison R.E., Frumhoff P.C., Canadell J.G., Field C.B., Nepstad D.C., Hayhoe K., Avissar R., Curran L.M., Friedlingstein J.C.D., Nobre C. (2007). Tropical forests and climate change. *Science*, 316, 985-986.

- Harrison A.G., Coll R.K. (2007). *Using analogies in middle and secondary science classrooms: The FAR guide - an interesting way to teach with analogies*. Carlifornia, USA: Corwin Press.
- Hobson P.N., Shaw B.G. (1973). The anaerobic digestion of waste from an intensive pig unit. *Water Research*, 7, 437–449.
- Iyagba1 E.T., Mangibo I.A., Mohammad Y.S. (2009). The study of cow dung as co-substrate with rice husk in biogas production. *Scientific Research and Essay*, 4(9), 861-866.
- Kaisu M., Mika J., Kari S., Markku L., Carl-Johan F., Arto R. (2008). *Controlled combustion of low quality gas mixtures*. Finland: Helsinki University of Technology.
- Kalia, A. K. and Kanwar S.S. (1998). Long term evaluation of a fixed dome Janata biogas plant in hilly conditions. *Bioresour. Technol.*, 65, 61-63.
- Kambewa P., Mataya B., Sichinga K., Johnson T. (2007). *Charcoal: the reality-A study of charcoal consumption, trade and production in Malawi*. London, UK: International Institute for Environment and Development.
- Karki A.B., Shretha J.N., Bajgain S. (2005). *Biogas as a Renewable Source of Energy in Nepal-Theory and and Development*. Kathmandu: BSP Nepal.
- Khoiyangbam R. S., Kumar S., Jain M.C., Gupta N., Kumar A., Kumar V. (2004). Methane emission from fixed dome biogas plants in hilly and plain regions of northern India. *Bioresour. Technol.*, 95, 35-39.
- Kraemer S. (1996). *Rural Electrification from Biogas in Malawi: A prefeasibility study financed by Unido*. Lilongwe: UNDP/UNIDO.

- Lang A. (2014). Heat Transfer and Energy. Accessed on 6/01/2014 from: <http://www.aos.wisc.edu/~aalopez/aos101/wk5.html>.
- Laurisden M.I. (1998). Evaluation of the impact on women's lives of the introduction of low cost polyethylene bio-digesters on farms in villages around Ho Chi Minh City, Viet Nam. *Livestock Research for Rural Development*, 10(3). www.cpar.org.co.
- Luer M. (2010). *Installation Manual for Low Cost Polyethylene Tube Digesters*. Accessed on 11/04/2012 from: www.energypedia.org.
- Malawi Industrial Research and Technology Development Centre (1996). *Report on Coordination Forum for Biogas Technology Promotion Programme*. Blantyre: MIRTDC.
- Marti-Herrero J. (2011). Reduced hydraulic retention times in low cost tubular digesters: Two issues. *Biomass and Bioenergy*, 35, 4481- 4484.
- Marti-Herrero J. and Supriano J. (2012). Design methodology for low cost tubular digesters. *Bioresource Technology*, (108), 21–27.
- McGarry M.H., Stainforth J. (1978). *Fertilizer and Biogas Production from Human and Farm Wastes in The People's Republic of China*. Ottawa, Canada: International Research Development Centre.
- Mlatho J.S.P., Henry M.T.E., Jones S.A. (2005). User's Perceptions of Crop Residues as a Fuel Rural Households: A Case Study of Zomba District, Malawi. *Malawi Journal of Sci. & Tech.*, 7, 59- 66.
- Mshandete A.M. and W. Parawira. (2009). Biogas technology research in selected sub-Saharan African countries: A review. *African journal of biotechnology*, 8 (2), 116- 125.

- Nasir I. M, Mohd Ghazi T.I, Omar R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Eng. Life Sci.*, 3, 258–269.
- Park K. H. and Riddle C.W. (2010). Methane emission patterns from stored liquid swine manure. *Asian Australas. J. Anim. Sci.*, 23, 1229-1235.
- Perrigault T., Weatherford V., Martí-Herrero J., Poggio D. (2012). Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. *Bioresour. Technol.*, 124, 259-268.
- Pham C.H., Vu C.C., Sommer S.G., Bruun S. (2014). Factors Affecting Process Temperature and Biogas Production in Small-scale Rural Biogas Digesters in Winter in Northern Vietnam. *Asian Australas. J. Anim. Sci.*, 27, 1050-1056.
- Philip T. and Itodo I. (2007). Nomograph for Determining Temperatures in Anaerobic Digesters from Ambient Temperatures in the Tropics. *Agricultural Engineering International*, 60 (10), 122-128.
- Pound B., Done F., Preston T.R. (1981). Biogas Production from Mixtures of Cattle Slurry and Pressed Sugarcane Stalk with or without Urea. *Tropical Animal Production*, 11- 27.
- Rajendran K., Aslanzadeh S. and Taherzadeh M.J. (2012). Household Biogas Digesters —A Review. *Energies*, 5, 2911-2942.
- Rehfuess E., (2006). Fuel for Life: Household Energy and Health. France: World Health Organization.
- Rodriguez L. and Preston T.R. (1997). *Biodigester installation manual*. Accessed on 23/2/2011 from:
<http://www.fao.org/ag/aga/agap/frg/Recycle/biodig/manual.htm>.

- San Thy and Preston T. R. (2003). Evaluation of the effluent from different retention times as fertilizer for growing water spinach (*Ipomoea aquatica*). Accessed on 12/04/2012 from: <http://www.mekarn.org/msc2001-03/theses03/santexp2.htm>.
- Sasse L., Kellner C., and Kimaro A. (1991). *An improved Biogas Unit for Developing Countries*. Braunschweig, Germany: Vieweg & Sohn Verlagsgesellschaft mbH.
- Schnurer A. and Jarvis A. (2009). *Microbiological handbook for biogas plants*. Sweden: Swedish Gas Centre.
- Stout B.A. and Best G. (2001). Effective Energy Use and Climate Change: Needs of Rural Areas in Developing Countries. *Agricultural Engineering International: the CIGR Journal of Scientific Research and Development*, 34, 231- 238.
- Tembo S. (2010). *Performance evaluation of biogas plants installed in Malawi*. Unpublished bachelors thesis, Mzuzu University.
- Test and Training Centre for Renewable Energy Technologies (2012). *Progress report on implementation of the fight against climate change – Choma/Chigwere project*. Mzuzu: Mzuzu University.
- Werner U., Stohr U., and Hees N. (1989). *Biogas Plants in Animal Husbandry-A Practical Guide*. Braunschweig-Germany: Friedr. Vieweg & Sohn.
- World Bank (2012). *Malawi country overview*. Accessed on 28/11/2012 from: www.worldbank.org.
- World Health Organization (WHO) (2005). *Indoor air pollution from solid fuels and risk of low birth weight and stillbirth*. Report from a symposium, Johannesburg.

Xie S. (2012). *Evaluation of biogas production from anaerobic digestion of pig manure and grass silage*. Unpublished doctoral thesis, National University of Ireland, Galway.

Zomba District Assembly (2009). *Zomba District Social Economic Profile*. Zomba: Department of Planning and Development.

APPENDICES

APPENDIX A1: GAS PRODUCTIONA DATA

DATE	Amount of Gas produced (litres)			
	Digester 1a_Pig dung_Open	Digester 1b_Pig dung_GH	Digester 2a_Goatstomach_Open	Digester 2b_Goatstomach_GH
6/5/2013	21	27	33	9
7/5/2013	6	9	30	45
8/5/2013	33	27	24	30
9/5/2013	24	21	36	68
10/5/2013	45	27	54	63
11/5/2013	45	57	63	60
12/5/2013	48	30	57	66
13/5/2013	51	33	54	63
15/5/2013	24	12	21	30
16/5/2013	21	24	33	48
17/5/2013	24	33	48	51
18/5/2013	30	33	36	30
19/5/2013	27	24	33	39
20/5/2013	21	24	33	36
21/5/2013	21	27	30	39
22/5/2013	36	39	33	42
23/5/2013	33	42	33	27
24/5/2013	33	39	30	24
25/5/2013	24	21	30	27
26/5/2013	33	36	27	27
27/5/2013	36	33	27	30
28/5/2013	39	36	36	39
29/5/2013	39	39	42	36
30/5/2013	42	39	39	42
1/6/2013	39	42	42	45
2/6/2013	36	39	34	42
3/6/2013	39	39	42	45
4/6/2013	36	42	42	39
5/6/2013	39	39	36	36
6/6/2013	39	36	42	39

APPENDIX A2: pH DATA

DATE	pH					
	Digester 1a_Pig dung_Open	Digester 1b_Pig dung_GH	Digester 2a_Goatstom ach_Open	Digester 2b_Goatstom ach_GH	Digester 3a_Food waste_Open	Digester 3b_Food Waste_GH
2/4/2013	7.4	7.6	7.1	7.0	4.5	3.8
6/4/2013	7.2	7.7	6.9	7.0	4.0	3.7
18/4/2013	7.2	7.7	6.8	7.0	3.8	3.8
29/4/2013	7.2	7.5	7.0	7.0	4.4	3.7
6/5/2013	7.2	7.5	7.0	7.1	3.4	3.9
11/5/2013	7.2	7.3	6.9	7.0	4.0	3.7
15/5/2013	7.0	7.6	6.8	7.0	4.0	3.7
19/5/2013	7.3	8.0	7.1	7.2	3.8	4.2
22/5/2013	7.4	8.1	7.1	7.1	3.7	4.2
26/5/2013	7.4	8.1	7.0	7.1	3.8	4.2
1/6/2013	7.3	7.4	7.0	7.1	3.7	4.0
6/6/2013	7.3	7.4	7.2	7.1	3.8	4.0

APPENDIX A3: AMBIENT AND GREENHOUSE TEMPERATURE DATA

A*=Ambient, 1b* = Greenhouse on pig dung digester, 2b*=Greenhouse on goat stomach wastes digester,
3b*=Greenhouse on food wastes digester

Date	Time	Temperature inside greenhouses (C°)				Date	Time	Temperature inside greenhouses (C°)			
		A*	1b*	2b*	3b*			A*	1b*	2b*	3b*
22/03/2013	6:00	18	23	23	21	24/03/2013	6:00	18	21	22	23
	7:00	19	23	23	20		7:00	18	21	23	23
	8:00	19	22	22	20		8:00	21	21	22	23
	9:00	21	22	22	21		9:00	24	21	22	23
	10:00	23	22	22	24		10:00	25	22	22	22
	11:00	25	22	22	23		11:00	28	23	23	23
	12:00	26	22	23	25		12:00	27	23	24	27
	13:00	26	24	23	25		13:00	26	26	23	23
	14:00	26	23	23	26		14:00	26	23	24	26
	15:00	26	23	24	25		15:00	26	24	23	24
	16:00	25	25	23	24		16:00	25	23	23	24
	17:00	26	25	23	25		17:00	25	23	23	23
	18:00	25	25	23	25		18:00	24	24	23	24
	19:00	20	23	23	24		19:00	20	24	24	24
	20:00	20	22	22	23		20:00	18	22	23	24
	21:00	21	22	21	21		21:00	20	21	23	24
	22:00	21	21	19	18		22:00	19	23	23	23
	23:00	20	20	19	18		23:00	17	23	23	24
	0:00:00	19	20	20	19		0:00:00	18	23	23	23
	1:00	18	19	19	20		1:00	19	23	23	23
	2:00:00	18	18	18	19		2:00:00	19	23	23	23
	3:00:00	18	17	17	18		3:00:00	18	23	23	23
	4:00:00	17	17	18	18		4:00:00	18	22	23	23
	5:00	17	18	17	17		5:00	18	23	22	23
23/03/2013	6:00	17	23	23	24	25/03/2013	6:00	18	20	22	23
	7:00	19	22	22	23		7:00	19	22	22	23
	8:00	21	22	22	22		8:00	20	21	22	23
	9:00	22	22	22	23		9:00	24	21	22	23
	10:00	23	21	22	22		10:00	25	22	22	23
	11:00	24	22	23	23		11:00	28	23	22	24
	12:00	24	23	22	23		12:00	28	23	23	23
	13:00	25	23	23	23		13:00	25	23	23	24
	14:00	25	21	22	23		14:00	27	24	23	23
	15:00	24	23	23	23		15:00	26	24	23	24
	16:00	24	24	24	25		16:00	25	23	23	24
	17:00	23	25	24	24		17:00	24	25	23	24
	18:00	23	24	24	24		18:00	23	24	24	23

	19:00	22	23	23	23		19:00	22	23	24	23
	20:00	22	23	22	22		20:00	22	23	23	24
	21:00	20	22	19	22		21:00	23	24	25	23
	22:00	21	22	22	21		22:00	20	24	24	22
	23:00	22	22	22	22		23:00	21	23	23	22
	0:00:00	19	23	22	22		0:00:00	20	23	23	23
	1:00	19	22	20	21		1:00	20	22	23	24
	2:00:00	19	21	21	22		2:00:00	18	23	23	24
	3:00:00	20	20	21	22		3:00:00	19	23	23	23
	4:00:00	21	20	20	19		4:00:00	18	22	23	23
	5:00	17	20	21	18		5:00	18	22	23	23
26/03/ 2013	6:00	19	23	23	23	28/03/ 2013	6:00	18	18	20	19
	7:00	19	22	23	23		7:00	19	20	19	19
	8:00	19	22	23	23		8:00	20	20	20	21
	9:00	20	21	20	23		9:00	23	22	22	22
	10:00	21	22	22	23		10:00	23	23	23	23
	11:00	24	22	23	23		11:00	25	26	25	24
	12:00	24	22	23	23		12:00	25	27	27	27
	13:00	24	23	23	24		13:00	27	28	25	24
	14:00	24	23	23	23		14:00	28	29	24	28
	15:00	24	24	23	23		15:00	27	28	27	27
	16:00	22	23	23	23		16:00	27	26	25	27
	17:00	22	23	23	23		17:00	24	25	25	25
	18:00	22	23	23	23		18:00	25	23	24	24
	19:00	21	23	23	23		19:00	22	24	23	23
	20:00	20	23	23	23		20:00	20	23	22	22
	21:00	20	23	23	23		21:00	17	20	22	21
	22:00	20	23	23	23		22:00	19	19	23	22
	23:00	20	22	23	22		23:00	18	18	24	23
	0:00:00	17	22	23	23		0:00:00	19	21	20	20
27/03/ 2013	1:00	18	22	23	21	29/03/ 2013	1:00	19	20	20	19
	2:00:00	22	22	23	23		2:00:00	18	20	21	19
	3:00:00	18	22	23	22		3:00:00	17	20	22	18
	4:00:00	15	22	22	23		4:00:00	18	21	22	17
	5:00	17	22	22	23		5:00	17	20	20	17
	6:00	19	21	22	22		6:00	17	18	20	19
	7:00	17	22	21	22		7:00	19	20	21	20
	8:00	20	22	21	22		8:00	20	21	22	22
	9:00	23	23	22	21		9:00	23	23	24	23
	10:00	24	24	21	21		10:00	25	27	23	26
	11:00	28	21	22	25		11:00	25	30	26	26
	12:00	26	22	22	22		12:00	28	30	30	26
	13:00	25	22	22	23		13:00	31	32	29	31
	14:00	27	27	25	26		14:00	29	29	31	30
	15:00	26	26	27	27		15:00	28	31	24	29

	16:00	24	25	23	24		16:00	27	24	28	28
	17:00	24	25	25	26		17:00	26	25	27	27
	18:00	23	24	24	24		18:00	24	26	26	25
	19:00	21	23	23	24		19:00	23	26	25	25
	20:00	20	23	26	23		20:00	21	23	24	24
	21:00	20	19	21	20		21:00	22	24	23	23
	22:00	20	20	19	20		22:00	20	24	22	24
	23:00	20	19	19	21		23:00	21	23	21	23
	0:00:00	18	19	22	23		0:00:00	20	22	23	22
	1:00	18	19	21	23		1:00	20	23	23	24
	2:00:00	18	20	20	20		2:00:00	20	20	22	21
	3:00:00	17	18	19	19		3:00:00	19	20	21	20
	4:00:00	17	18	17	18		4:00:00	17	20	20	19
	5:00	17	17	18	17		5:00	17	21	19	18
14/4/2013	6:00	18	20	20	19	16/4/2013	6:00	16	19	18	17
	7:00	19	20	21	21		7:00	19	19	20	19
	8:00	20	22	21	23		8:00	20	20	21	21
	9:00	22	24	23	23		9:00	23	24	23	24
	10:00	25	26	24	26		10:00	24	25	25	25
	11:00	26	28	28	24		11:00	27	29	28	29
	12:00	28	30	25	27		12:00	27	30	28	26
	13:00	27	29	24	26		13:00	27	28	27	27
	14:00	28	28	25	25		14:00	24	26	26	26
	15:00	25	27	26	24		15:00	26	26	26	26
	16:00	24	24	25	23		16:00	26	36	24	26
	17:00	25	26	25	22		17:00	24	35	26	26
	18:00	22	24	24	20		18:00	23	25	24	23
	19:00	17	20	21	22		19:00	23	23	23	24
	20:00	18	23	21	28		20:00	21	22	22	22
	21:00	20	22	22	22		21:00	20	21	23	23
	22:00	20	22	20	21		22:00	18	20	20	21
	23:00	19	22	20	21		23:00	17	19	21	22
	0:00:00	18	20	22	20		0:00:00	17	18	22	23
	1:00	18	22	20	20		1:00	18	21	21	21
	2:00:00	18	19	20	20		2:00:00	18	20	21	22
	3:00:00	15	20	20	19		3:00:00	19	20	22	22
	4:00:00	17	20	19	22		4:00:00	19	20	20	21
	5:00	15	16	18	19		5:00	20	24	20	22
15/4/2013	6:00	15	18	21	18	17/4/2013	6:00	18	18	22	19
	7:00	17	19	20	19		7:00	17	22	20	21
	8:00	18	22	20	21		8:00	18	19	19	19
	9:00	23	23	23	23		9:00	18	20	21	21
	10:00	25	25	26	27		10:00	18	20	21	20
	11:00	26	27	24	25		11:00	19	20	22	20
	12:00	27	29	28	29		12:00	18	20	20	20

	13:00	27	30	25	27		13:00	19	20	22	21
	14:00	28	31	28	29		14:00	19	20	20	20
	15:00	27	28	27	28		15:00	20	21	21	21
	16:00	26	28	28	27		16:00	19	20	20	20
	17:00	25	26	25	25		17:00	19	20	21	19
	18:00	26	24	23	24		18:00	21	22	21	23
	19:00	23	22	22	22		19:00	19	18	19	24
	20:00	18	23	20	22		20:00	19	20	20	19
	21:00	18	22	21	20		21:00	17	19	20	20
	22:00	20	20	22	21		22:00	17	17	21	19
	23:00	21	19	22	20		23:00	18	18	20	19
	0:00:00	16	18	18	18		0:00:00	17	18	20	18
	1:00	16	21	20	19		1:00	18	19	20	18
	2:00:00	15	19	19	20		2:00:00	17	18	19	17
	3:00:00	17	19	18	18		3:00:00	17	18	20	15
	4:00:00	16	19	22	22		4:00:00	16	20	19	19
	5:00	16	20	19	20		5:00	16	19	17	17
18/5/2013	6:00	15	16	17	18	20/5/2013	6:00	15	17	16	16
	7:00	16	18	17	17		7:00	15	16	15	16
	8:00	16	19	19	19		8:00	16	17	17	17
	9:00	17	19	19	18		9:00	17	18	18	17
	10:00	19	19	20	19		10:00	19	20	19	20
	11:00	19	19	19	20		11:00	20	19	19	20
	12:00	20	21	22	21		12:00	21	20	19	21
	13:00	20	21	22	21		13:00	23	21	20	21
	14:00	20	21	21	22		14:00	21	21	20	21
	15:00	23	24	21	22		15:00	22	22	20	20
	16:00	21	22	22	21		16:00	21	21	21	20
	17:00	20	21	20	20		17:00	19	22	20	20
	18:00	17	19	20	19		18:00	17	18	19	19
	19:00	17	18	19	18		19:00	17	19	18	18
	20:00	17	18	17	17		20:00	15	15	16	17
	21:00	17	17	18	18		21:00	14	15	18	16
	22:00	16	18	17	18		22:00	14	16	17	15
	23:00	16	18	16	16		23:00	15	16	15	15
	0:00:00	16	17	17	17		0:00:00	13	16	14	15
19/5/2013	1:00	15	17	16	18	21/5/2013	1:00	12	14	13	15
	2:00:00	15	16	17	16		2:00:00	13	16	13	15
	3:00:00	15	16	18	19		3:00:00	12	14	13	15
	4:00:00	15	17	18	17		4:00:00	13	15	14	15
	5:00	15	16	17	17		5:00	13	15	15	16
	6:00	15	17	16	16		6:00	15	16	15	16
	7:00	15	16	16	16		7:00	15	16	16	16
	8:00	15	17	17	17		8:00	16	18	17	17
	9:00	15	17	19	17		9:00	17	18	18	18

	10:00	16	17	19	16		10:00	19	20	19	19
	11:00	17	18	17	18		11:00	20	21	20	21
	12:00	17	18	18	18		12:00	22	21	24	23
	13:00	15	18	19	18		13:00	25	26	26	24
	14:00	16	19	19	19		14:00	25	26	24	22
	15:00	18	19	18	19		15:00	23	26	25	24
	16:00	17	19	18	19		16:00	25	25	23	22
	17:00	17	18	19	18		17:00	20	23	21	21
	18:00	16	17	17	18		18:00	18	21	20	21
	19:00	15	17	16	18		19:00	18	20	20	19
	20:00	14	16	15	16		20:00	17	18	19	19
	21:00	13	14	15	16		21:00	17	18	19	18
	22:00	13	13	14	15		22:00	17	19	18	18
	23:00	13	16	14	15		23:00	16	18	17	19
	0:00:00	13	14	14	15		0:00:00	16	18	19	18
	1:00	12	14	13	16		1:00	17	19	17	18
	2:00:00	12	14	14	15		2:00:00	14	18	18	17
	3:00:00	14	15	15	15		3:00:00	15	18	17	16
	4:00:00	14	15	15	17		4:00:00	13	15	17	15
	5:00	15	16	15	16		5:00	13	15	16	16
23/5/ 2013	6:00	13	15	15	16	25/5/2 013	6:00	10	12	14	15
	7:00	14	15	16	16		7:00	12	15	16	19
	8:00	17	17	18	17		8:00	14	15	16	15
	9:00	20	21	21	20		9:00	17	18	17	17
	10:00	21	22	20	22		10:00	19	21	19	19
	11:00	23	25	24	24		11:00	20	22	21	21
	12:00	23	22	20	21		12:00	22	22	20	21
	13:00	21	22	21	21		13:00	23	23	21	24
	14:00	22	24	20	21		14:00	23	25	22	23
	15:00	20	21	21	21		15:00	22	24	23	23
	16:00	20	21	21	19		16:00	22	22	22	22
	17:00	18	20	20	19		17:00	22	23	21	21
	18:00	18	20	20	19		18:00	20	22	19	19
	19:00	18	19	19	18		19:00	15	16	17	20
	20:00	17	18	19	18		20:00	13	15	18	17
	21:00	17	18	18	17		21:00	14	16	15	15
	22:00	16	17	19	17		22:00	13	15	17	16
	23:00	16	18	17	18		23:00	13	15	16	15
	0:00	15	17	16	17		0:00	12	14	18	15
	1:00	13	15	14	18		1:00	11	15	18	15
	2:00:00	13	14	15	16		2:00:00	10	14	16	13
	3:00:00	14	15	14	16		3:00:00	10	12	13	16
	4:00:00	13	16	17	15		4:00:00	10	12	15	14
	5:00	14	15	16	17		5:00	10	14	12	14
24/5/	6:00	14	15	14	15	26/5/2	6:00	10	13	12	13

2013	7:00	15	16	18	17	013	7:00	12	13	16	14
	8:00	17	18	18	17		8:00	15	15	16	15
	9:00	18	19	19	18		9:00	17	18	17	16
	10:00	21	19	19	19		10:00	20	22	18	19
	11:00	22	20	20	20		11:00	23	22	20	21
	12:00	22	23	21	21		12:00	23	23	20	20
	13:00	23	23	20	22		13:00	24	24	23	23
	14:00	23	23	21	21		14:00	23	26	20	22
	15:00	23	22	21	22		15:00	26	24	25	23
	16:00	22	22	22	21		16:00	21	23	20	22
	17:00	19	20	20	20		17:00	19	19	20	21
	18:00	18	20	19	20		18:00	16	18	19	18
	19:00	17	17	17	17		19:00	13	16	16	18
	20:00	15	19	17	18		20:00	13	16	17	16
	21:00	14	16	14	15		21:00	12	15	18	15
	22:00	12	15	17	16		22:00	11	15	13	15
	23:00	13	15	14	14		23:00	11	15	18	16
	0:00:00	12	16	14	15		0:00:00	11	14	13	14
	1:00	13	15	16	15		1:00	10	13	14	13
	2:00:00	12	14	13	16		2:00:00	10	10	11	12
	3:00:00	12	13	14	15		3:00:00	10	12	11	12
	4:00:00	11	14	13	14		4:00:00	10	13	12	13
	5:00	11	15	14	14		5:00	11	12	12	13
27/5/2013	6:00	10	10	14	15	29/5/2013	6:00	12	13	13	17
	7:00	10	13	16	15		7:00	13	14	17	16
	8:00	15	15	16	15		8:00	17	17	18	17
	9:00	17	18	17	16		9:00	20	19	18	19
	10:00	21	23	20	19		10:00	23	24	21	21
	11:00	25	24	20	20		11:00	24	25	21	21
	12:00	26	27	20	21		12:00	26	28	27	25
	13:00	26	27	27	24		13:00	27	30	28	25
	14:00	29	30	22	25		14:00	27	31	28	27
	15:00	25	29	26	24		15:00	26	30	26	26
	16:00	23	24	24	22		16:00	23	25	24	24
	17:00	19	21	21	21		17:00	19	24	24	23
	18:00	16	18	17	18		18:00	17	20	21	19
	19:00	14	19	17	18		19:00	16	19	19	18
	20:00	14	17	17	18		20:00	15	18	20	15
	21:00	14	15	15	17		21:00	14	17	16	19
	22:00	13	15	17	16		22:00	14	15	17	17
	23:00	12	14	15	18		23:00	13	14	16	16
	0:00:00	12	13	15	14		0:00:00	12	16	18	15
	1:00	12	14	15	16		1:00	12	15	18	18
	2:00:00	12	12	12	12		2:00:00	12	15	16	14
	3:00:00	12	13	14	16		3:00:00	12	14	15	16

	4:00:00	11	14	13	13		4:00:00	12	15	16	16
	5:00	10	12	13	17		5:00	12	15	16	16
28/5/2013	6:00	10	13	13	13	30/5/2013	6:00	10	13	11	15
	7:00	13	14	13	15		7:00	13	14	16	17
	8:00	21	22	18	19		8:00	16	17	18	16
	9:00	22	24	20	20		9:00	18	19	18	18
	10:00	21	24	20	21		10:00	22	23	20	21
	11:00	24	25	22	20		11:00	23	24	21	21
	12:00	24	25	22	20		12:00	24	26	21	21
	13:00	25	28	22	24		13:00	25	24	21	24
	14:00	25	25	22	24		14:00	26	28	22	24
	15:00	24	28	25	22		15:00	27	29	27	25
	16:00	23	25	23	23		16:00	24	26	25	24
	17:00	19	22	21	21		17:00	19	22	21	22
	18:00	17	20	20	19		18:00	17	20	20	19
	19:00	15	17	17	18		19:00	14	18	17	18
	20:00	15	17	18	17		20:00	17	17	18	19
	21:00	16	18	17	17		21:00	15	16	15	15
	22:00	16	17	17	16		22:00	13	16	17	18
	23:00	15	17	16	18		23:00	12	15	17	16
	0:00:00	15	15	17	16		0:00:00	14	15	19	18
	1:00	13	16	17	16		1:00	12	14	16	18
	2:00:00	13	16	18	15		2:00:00	12	15	16	14
	3:00:00	13	15	17	18		3:00:00	13	15	16	15
	4:00:00	12	14	16	18		4:00:00	12	16	14	17
	5:00	12	16	18	14		5:00	10	14	17	16
31/5/2013	6:00	10	12	16	15	1/6/2013	6:00	10	12	13	10
	7:00	13	14	15	15		7:00	10	12	12	13
	8:00	16	16	18	17		8:00	15	15	16	15
	9:00	20	19	19	18		9:00	18	18	19	19
	10:00	23	23	21	22		10:00	22	20	23	23
	11:00	25	25	22	24		11:00	22	23	23	22
	12:00	25	27	21	24		12:00	24	23	24	25
	13:00	26	29	26	25		13:00	24	26	27	26
	14:00	27	30	27	25		14:00	24	27	28	27
	15:00	26	28	26	25		15:00	26	29	26	25
	16:00	26	27	25	24		16:00	24	27	28	22
	17:00	19	23	21	22		17:00	22	24	22	21
	18:00	16	19	19	19		18:00	18	21	20	20
	19:00	16	19	18	20		19:00	15	17	16	17
	20:00	16	16	17	16		20:00	14	18	15	15
	21:00	14	18	16	16		21:00	12	14	13	14
	22:00	14	16	15	17		22:00	13	13	13	13
	23:00	14	16	15	16		23:00	11	12	13	12
	0:00:00	11	13	13	14		0:00:00	10	15	13	14

2/6/2013	1:00	11	13	13	18	3/6/2013	1:00	10	12	12	13
	2:00:00	11	14	15	14		2:00:00	10	11	11	12
	3:00:00	11	14	15	19		3:00:00	10	11	11	11
	4:00:00	10	13	15	16		4:00:00	9	10	10	11
	5:00	10	13	13	14		5:00	10	11	11	12
	6:00	10	13	14	14		6:00	10	13	12	10
	7:00	11	13	14	15		7:00	10	12	12	11
	8:00	16	17	16	16		8:00	17	18	18	12
	9:00	20	19	20	21		9:00	21	23	23	23
	10:00	24	21	23	22		10:00	22	23	24	24
	11:00	25	25	23	24		11:00	22	23	22	21
	12:00	25	26	25	25		12:00	23	26	23	25
	13:00	26	29	28	23		13:00	25	28	26	26
	14:00	29	33	26	26		14:00	25	28	26	23
	15:00	27	28	26	23		15:00	25	27	27	27
	16:00	22	26	24	23		16:00	23	25	24	23
	17:00	18	24	20	20		17:00	19	21	20	21
	18:00	14	14	15	16		18:00	15	19	18	18
	19:00	12	16	17	15		19:00	15	18	17	18
	20:00	12	16	18	14		20:00	13	15	14	16
	21:00	12	16	13	14		21:00	13	14	16	15
	22:00	12	15	14	14		22:00	14	15	15	16
	23:00	10	14	13	14		23:00	13	16	14	15
3/6/2013	0:00:00	10	13	14	12	5/6/2013	0:00:00	13	14	15	16
	1:00	11	13	14	12		1:00	12	15	14	13
	2:00:00	10	13	12	16		2:00:00	12	13	13	18
	3:00:00	11	12	14	16		3:00:00	10	15	13	14
	4:00:00	10	12	14	16		4:00:00	10	14	15	13
	5:00	10	12	10	14		5:00	10	13	14	13
	6:00	10	14	12	15		6:00	10	13	14	15
	7:00	13	14	16	15		7:00	13	14	13	16
	8:00	16	16	15	18		8:00	17	17	17	17
	9:00	20	18	19	17		9:00	18	19	18	19
	10:00	23	21	23	22		10:00	20	23	19	19
	11:00	22	26	25	25		11:00	20	21	22	21
	12:00	28	25	27	24		12:00	19	20	21	19
	13:00	24	27	26	27		13:00	21	22	21	20
	14:00	26	32	27	25		14:00	21	22	21	21
	15:00	25	27	27	25		15:00	20	21	20	20
	16:00	22	24	24	24		16:00	19	20	20	20
	17:00	18	21	20	20		17:00	19	20	20	19
	18:00	16	20	18	19		18:00	19	19	19	19
	19:00	14	18	18	19		19:00	16	18	17	19
	20:00	14	15	16	13		20:00	15	16	18	18
	21:00	12	16	14	14		21:00	14	17	16	17

		22:00	12	15	16	14		22:00	13	16	17	18
		23:00	10	14	13	15		23:00	12	16	18	17
6/6/2013		0:00:00	12	15	13	14		0:00:00	13	15	14	17
		1:00	12	14	15	16		1:00	12	14	15	16
		2:00:00	12	15	14	15		2:00:00	12	15	13	15
		3:00:00	10	12	16	14		3:00:00	10	14	12	13
		4:00:00	10	13	12	13		4:00:00	10	13	12	14
		5:00	10	13	12	15		5:00	10	13	12	15
		6:00	10	12	13	14		6:00				
		7:00	10	12	12	13		7:00				
		8:00	15	15	15	15		8:00				
		9:00	17	18	17	18		9:00				
		10:00	19	19	21	19		10:00				
		11:00	22	21	23	22		11:00				
		12:00	23	22	26	22		12:00				
		13:00	25	26	26	23		13:00				
		14:00	25	30	27	25		14:00				
		15:00	24	28	26	24		15:00				
		16:00	22	24	24	23		16:00				
		17:00	20	22	21	21		17:00				
		18:00	15	19	20	17		18:00				
		19:00	15	19	16	17		19:00				
		20:00	14	18	15	15		20:00				
		21:00	13	15	18	14		21:00				
		22:00	14	15	14	16		22:00				
		23:00	13	14	16	15		23:00				
		0:00:00	12	15	14	15		0:00:00				
		1:00	12	14	15	14		1:00				
		2:00:00	13	14	14	15		2:00:00				
		3:00:00	12	15	16	15		3:00:00				
		4:00:00	12	14	15	16		4:00:00				
		5:00	13	14	13	17		5:00				

APPENDIX A4: DIGESTER PERFORMANCE DATA RECORDING FORM DESIGN

Date:.....

Day No:.....

TIME Hours	TEMPERATURE(C°)				GAS PRODUCTION (Litres)						PRESSURE(cm of water column)						pH					
	Digester ID				Digester ID						Digester ID						Digester ID					
	A*	D1b	D2b	D3b	D1a	D1b	D2a	D2b	D3a	D3b	D1a	D1b	D2a	D2b	D3a	D3b	D1a	D1b	D2a	D2b	D3a	D3 b
06:00																						
07:00																						
08:00																						
09:00																						
10:00																						
11:00																						
12:00																						
13:00																						
14:00																						
15:00																						
16:00																						
17:00																						
18:00																						
19:00																						
20:00																						
21:00																						
22:00																						
23:00																						
00:00																						
01:00																						
02:00																						
03:00																						
04:00																						
05:00																						