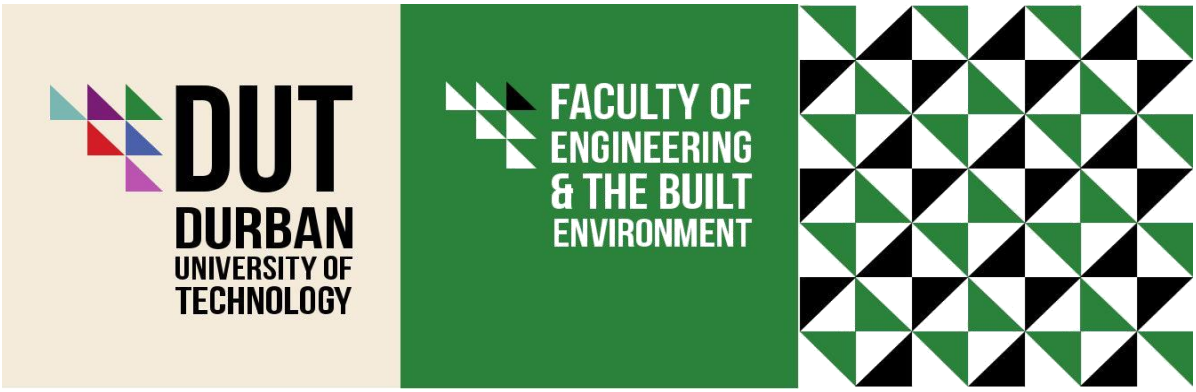


# A Study of biogas generation from poultry litter and its impurity removal

A thesis submitted in fulfilment of academic requirements for the degree of

**Master of Engineering**

**Durban University of Technology**

**Faculty of Engineering and the Built Environment,**

**Department of Chemical Engineering,**

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**Date: January 2019**

**Supervisors: I J Lazarus, G K Reddy and R Singh**

# Declaration

I Ighodaro Osagie, student number (21451006), hereby declare that unless indicated, this thesis titled: *A study of biogas generation from poultry litter and impurity removal* is the result of my own investigation and has not been submitted in part or in full for any other degree at another University or Institution.

Date: 17/11/2020 Signature [redacted]

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

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# Abstract

This study is focused on the anaerobic digestion of poultry waste to produce biogas. Waste was collected from three different poultry farms (Sekela farm, Emarldene and Parkside poultry industry) in Kwazulu-Natal, South Africa. The aim is to assess energy from poultry waste in Kwazulu-Natal and to enhance the process of biogas production by treating the impurities of sulphur content, moisture and carbon dioxide in the biogas. The objectives are: to determine the energy potential of poultry waste in Kwazulu-Natal region, to increase the energy density of the biogas by the removal of moisture content, incombustible and corrosive gas and to assess techno-economic feasibility of biogas generation from poultry waste.

1 kg of each waste was thoroughly mixed with 3 L of water and loaded into ten digesters with each water bath (thermal conductor) bearing two digesters. The slurry was investigated using water displacement method to determine biogas produced for a period of 21 days and at an average temperature of 30 $^0$C, 31 $^0$C, and 32 $^0$C respectively. Production started on the 3$^{rd}$ day for each digester at different temperatures (30 $^0$C, 31 $^0$C, and 32 $^0$C), and attained maximum value on the 14$^{th}$ and 15$^{th}$ days. The maximum amount of biogas produced was 265.6 ml at a temperature of 32 $^0$C from waste A (Sekela farm). At 32 $^0$C, an optimal biogas yield of 421.6 ml/g VS was observed from Sekela farm (poultry waste A) compared to Emarldene (370.10 ml/g) and Parkside poultry industry (349.10 ml/g) in KwaZulu-Natal.

Biogas was collected from the digester with the maximum volume of biogas produced using 100 µL gas syringe and was taking to Gas chromatography for characterization. The result showed that it was composed of about 57.71 % methane ($CH_4$), 26.8 % carbon dioxide ($CO_2$), 0.8 % nitrogen ($N_2$), traces of hydrogen sulfide ($H_2S$), fractions of water vapor, and other impurities which the detector was unable to quantify with an energy potential of 0.028 MJ/ml. Purification and Upgrade system was comprised of one column charged with steel wool (iron sponge), and two cylinders charged with pressurized water and silica gel to treat $H_2S$, $CO_2$, and water vapor in the biogas for improvement of its energy density. Biogas was collected from the purified system using gas syringe to the Gas chromatography for characterization and result showed that it is composed of about 84.56 % $CH_4$ and energy potential of 0.046 MJ/ml. The result confirmed that the biogas heating value/energy density was improved/increased using steel wool, pressurized water and silica gel as biogas contaminants removal.

Techno-economic studies were carried out to assess the techno-economic feasibility of a small-scale biogas plant using poultry waste in KwaZulu-Natal. A fixed dome digester was selected as the most convenient technology for the community. Result showed that 2,160 kWh per year of energy could be produced from about 4,000 kg of poultry waste and the payback time was eleven years and nine

months. It showed that it is techno-economically feasible to use a fixed dome digester for energy generation for domestic usage and is cost-effective.

In conclusion, poultry waste as a feedstock is suitable for anaerobic digestion, producing methane which can be used as an energy source and which can be purified to improve its energy potential. Biogas optimization is dependable on: temperature, physio-chemical characteristics of waste, pH and retention time e.g. at same temperature (either 30 $^0$C, 31 $^0$C or 32 $^0$C) and time, waste A production is higher than waste B and C because of its favorable physio-chemical characteristics and pH-value. It is deduced that the energy potential in poultry waste could be determine by treating the waste via anaerobic digestion and the increase in the energy density of the waste is dependable on temperature, pH, retention time and physio-chemical characteristics of the waste.

# Dedication

This research work is dedicated to: my loving family and wife: Imwenoghomwen Ighodaro and Deborah Edwards. I thank you all for the love and care throughout the period of my studies. The support and endurance you all have shown, making this study much easier to be completed. Our journey together has not only given me success in this work but has also strengthened my love for all of you. Unto GOD almighty, without your grace, mercy and divine direction this project will not have been a reality.

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# Table of Contents

**Declaration**……I

**Abstract**……II

**Dedication**……IV

**Acknowledgement**……V

**Table of Contents**……VI

**List of Tables**……X

**List of Figure**……XII

**List of Abbreviations**……XIV

**Chapter 1 - Introduction** 1

**1.1 Background** ……1

**1.2 Research Problem** ……3

**1.3 Selection of Substrate** ……4

**1.4 Aims and Objectives** ……4

**1.5 Research Approach** ……4

**1.6 Rational and Significant** ……5

**1.7 Thesis Organization** ……5

**Chapter 2 - Literature Review** 7

**2.1 Introduction** ……7

**2.2 Poultry Litter** ……7

**2.3 Poultry litter as an energy source**……8

**2.4 Biogas**……9

**2.5 Biogas production**……9

**2.6 Anaerobic Digestion** ……10

2.6.1 Hydrolysis……10

2.6.2 Acidogenesis……10

2.6.3 Acetogenic phase ……11

2.6.4 Methanogenic Phase ……11

2.6.5 Substrate for Anaerobic digestion process ……11

**2.7 Digestion Factors**……12

2.7.1 Temperature ……12

2.7.2 pH-values ……13

2.7.3 Hydraulic retention time ……13

2.7.4 Organic load .....14
2.7.5 Toxicity .....14
**2.8 Anaerobic digestion technology .....15**
2.8.1 Batch and Continuous (single and two stage) mode feeding systems .....15
2.8.2 Wet and Dry anaerobic digestion .....16
**2.9 Pre-Treatment of Solid waste.....16**
2.9.1 Pre-treatments for process enhancement .....17
2.9.1.1 Biological pre-treatment .....17
2.9.1.2 Mechanical pre-treatment .....18
2.9.1.3 Chemical pre-treatment .....18
**2.10 Economic aspects and current state application .....18**
**2.11 Total and Volatile Solids biogas potentials and Measurement…….....18**
**2.12 Inputs and their Characteristics .....19**
2.12.1 Carbon-to-Nitrogen (C/N) ratio .....19
2.12.2 Dilution and consistency of inputs .....20
2.12.3 Volatile solids (V.S) .....20
2.12.4 Total Kjeldahl Nitrogen (TKN)…….....……..……21
**2.13 Enhancement of Biogas Energy .....21**
**2.14 Purification and Upgrade ….....21**
2.14.1 Hydrogen sulfide ($H_2S$) .....21
2.14.2 Carbon dioxide ($CO_2$) scrubbing from biogas .....23
2.14.2.1 Physical absorption .....23
2.14.2.2 Chemical absorption .....23
2.14.2.3 Membrane separation .....23
2.14.2.4 Chemical conversion method.....24
2.14.3 Removal of Moist.....25
2.14.3.1 Physical drying methods (condensation) .....25
2.14.3.2 Chemical drying methods .....25
**2.15 Techno-economic feasibility…….....26**
**2.16 Summary .....28**

**Chapter 3 – Methodology** **30**

**3.1 Materials and Methods .....30**
**3.2 Digester Set-up Materials .....31**
**3.3 Experimental Apparatus .....31**
3.3.1 Economic Oven 80 Liter…….....……..……..……...31

3.3.2 Vacuum desiccator…….....…….……32
3.3.3 Ceramic crucible…….....……..…...32
3.3.4 Circulated laboratory water bath….....…….....…...33
3.3.5 Circulator…….....…….....…….…….…..33
**3.4 Analytical methods ……34**
3.4.1 Determination of Total solids……..……..……...34
3.4.2 Determination of Volatile solids……..……...…..……....34
3.4.3 pH-value……..……..……34
**3.5 Elemental analysis……..35**
**3.6 Sample Collection, Treatments and Experimental sequence .....35**
**3.7 Digester Preparation for Biogas production .....37**
3.7.1 Statistical Analysis of Biogas produced **….....39**
**3.8 Purification and Upgrade procedure** …….....39
3.8.1 Experimental Procedure for Purification and Upgrade of Biogas …...…….....……40
**3.9 Techno-economic Feasibility analysis..……..……....41**
3.9.1 Economic Analysis..……...……....41
3.9.2 Payback time (PB) .....42

**Chapter 4 – Results and Discussion 43**

**4.1 Feedstock Characteristic .....43**
**4.2 Biogas generation .....44**
**4.3 Cumulative biogas produced…….....49**
**4.4 Biogas yield…….....51**
**4.5 Effect of pH on biogas production.....……..…….55**
**4.6 Results from statistical analysis using one-way ANOVA .....58**
4.6.1 Effect of temperature on pH variation .....58
4.6.2 Effect of temperature on biogas production .....58
4.6.3 Effect of time on biogas production .....59
**4.7 Enhancing the energy density of biogas .....59**
4.7.1 Raw biogas analyzed using Gas chromatography .....59
4.7.2 Treatment of impurities) ...……..…… …… ……..……...60
**4.8 Techno-economic analysis .....63**
4.8.1 Input data .....63
4.8.1.1 Investment cost .....63
4.8.1.2 Operation and Maintenance (O & M) cost .....64
4.8.1.3 Income .....65

4.8.2 Economic analysis .....65
4.8.2.1 Investment cost, O & M cost .....65
4.8.2.2 Incomes.....66

**Chapter 5 – Conclusions and Recommendation** **68**

**Recommendations** **70**

**References** **71**

**Appendix A Laboratory Analysis** **87**
**Appendix B Biogas production at 30 $^0$C, 31 $^0$C, and 32 $^0$C** **90**
**Appendix C Statistical Analysis: One-way ANOVA** **100**
**Appendix D Heating value of biogas** **107**
**Appendix E Techno-economic Analysis** **110**

# List of Tables

Table 1.1 Estimated census of poultry birds in South Africa (South Africa Poultry Association, 2014) ……1
Table 1.2 Number of poultry farms in South Africa (South Africa Poultry Association, 2014) .....2
Table 1.3 Nutrient content in different type of organic waste (Bin Ahmad, 2010).....….....3
Table 2.1 Heating values of commercial fuels, and its corresponding biogas (Uz Zaman, 2007) .....…8
Table 2.2 Composition of biogas (Ali, et al., 2013; De Graaf and Fendler, 2010; Muzenda, 2014).....9
Table 2.3 Comparison of mesophilic and thermophilic anaerobic digestion (Bin Ahmad, 2010; Pudasaini, 2010) .....12
Table 2.4 Optimum biogas produced from different substrates at a giving HRT and at mesophilic temperature (Ojolo, et al., 2007) ….....14
Table 2.5 Toxic level of various inhibitors (Porras and Gebresenbet, 2003).....15
Table 2.6 Biogas potential of various types of organic waste (Porras and Gebresenbet, 2003).....19
Table 2.7 Organic materials and their C/N ratio (Porras and Muzenda, 2014).....20
Table 2.8 Time for boiling 500ml of water (Nallamothu, et al., 2013).....…21
Table 2.9 Advantages and disadvantages of techniques for removal of $H_2S$ (Ryckebosch, et al., 2011) ……..22
Table 2.10 Biogas upgrade (Farooq, et al., 2012) …….....23
Table 2.11 Advantages and disadvantages of techniques for removal of $CO_2$ (Ryckebosch, et al., 2011) …….....24
Table 2.12 Advantages and disadvantages of techniques for removal of water (Ryckebosch, et al., 2011) …….....26
Table 2.13 Standard for various family size of digester (Kumar, et al., 2014; Ugochukwu, 2011; Werner, et al., 1989; Wargert, 2009)…….27
Table 3.1 Equipment used for research .....30
Table 3.2 Constructed materials …….....31
Table 3.3 Limits of detection of gases (Rodrigues, et al., 2014) .....36
Table 3.4 Temperature of the water bath to slurry temperature .....38
Table 4.1 Poultry waste characteristics …….....43
Table 4.2 Composition of biogas from sample A, at 32 $^0$C before treatment of impurities using GC….....59
Table 4.3 Weight of iron oxide, silica gel before and after impurity treatment from 265.6mL of biogas produced from digester C, sample A at 32 $^0$C.…….....61
Table 4.4 Gas chromatography analysis of treated biogas after impurities treatment .....62

Table 4.5 Comparison of physical properties of natural gas and purified biogas from results and discussion (Chege, 2015; Saikkonen, 2006; Persson, et al., 2006; Department of Minerals and Energy, 2005; Demirbas, 2010) .....62
Table 4.6 Estimated investment cost of constructing 20 $m^3$ fixed dome digester …..….....…..…64
Table 4.7 Investment, O & M cost .…….....66
Table 4.8 Income from scenario II …….…….....…..66

# List of Figures

Figure 2.1 Fixed dome digester for poultry litter (Rauf, 2012) ……...…28
Figure 3.1 Economy oven 80 Liter …….....……..…..…31
Figure 3.2 Vacuum desiccator …….....……...…....32
Figure 3.3 Ceramic crucible …….....…….……...32
Figure 3.4 Circulated water bath …….....……33
Figure 3.5 CPM 50 circulator.…….....….……..33
Figure 3.6 Sample collection site …….....….……..37
Figure 3.7 Schematic diagram of water displacement method ….....37
Figure 3.8 Cross-section of experimental set-up..…….....….39
Figure 3.9 Biogas purification and upgrade …….....…...41
Figure 4.1a Biogas collection with time for poultry waste A, B, and C at an average temperature of 30 $^0$C ..…….…….…….....…45
Figure 4.1b Biogas collection with time for poultry waste A, B, and C at an average temperature of 31 $^0$C …...……...46
Figure 4.1c Biogas collection with time for poultry waste A, B, and C at an average temperature of 32 $^0$C ..……46
Figure 4.2a Comparing biogas collected from poultry waste sample A with time at 30 $^0$C, 31 $^0$C, and 32 $^0$C ...…….....……...47
Figure 4.2b Comparing biogas collected from poultry waste sample B with time at 30 $^0$C, 31 $^0$C, and 32 $^0$C ...……...……...48
Figure 4.2c Comparing biogas collected from poultry waste sample C with time at 30 $^0$C, 31 $^0$C, and 32 $^0$C ...….....48
Figure 4.3a Cumulative biogas produced with time for poultry waste A, B and C at an average temperature of 30 $^0$C ..……...49
Figure 4.3b Cumulative biogas produced with time for poultry waste A, B and C at an average temperature of 31 $^0$C ..……...……...50
Figure 4.3c Cumulative biogas produced with time for poultry waste A, B and C at an average temperature of 32 $^0$C …...……...……...50
Figure 4.4a Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 30 $^0$C ……...……..……51
Figure 4.4b Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 31 $^0$C ..……...……52
Figure 4.4c Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 32 $^0$C ..……...……52
Figure 4.5a Comparing biogas yield from poultry waste A at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time……53

Figure 4.5b Comparing biogas yield from poultry waste B at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time……54
Figure 4.5c Comparing biogas yield from poultry waste C at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time……54
Figure 4.6a pH-value of poultry waste sample A, B, and C at 30 $^0$C with retention time…….....55
Figure 4.6b pH-value of poultry waste sample A, B, and C at 31 $^0$C with retention time……...…..56
Figure 4.6c pH-value of poultry waste sample A, B, and C at 32 $^0$C with retention time……...…..56
Figure 4.7a Comparing pH-value of poultry waste sample A at 30 $^0$C, 31 $^0$C and 32 $^0$C with time.….57
Figure 4.7b Comparing pH-value of poultry waste sample B at 30 $^0$C, 31 $^0$C and 32 $^0$C with time…..57
Figure 4.7c Comparing pH-value of poultry waste sample C at 30 $^0$C, 31 $^0$C and 32 $^0$C with time…..58
Figure 4.8 Hydrogen Sulphide treatment …..…….....61
Figure 4.9 Moisture absorber …….....61

# Abbreviations

| | |
|---|---|
| % | Percentage |
| AD | Anaerobic digestion |
| C:N ratio | Carbon to Nitrogen ratio |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| GC | Gas Chromatography |
| GHG | Greenhouse Gas |
| GHG | Greenhouse gases |
| $H_2$ | Hydrogen |
| $H_2S$ | Hydrogen Sulfide |
| Hr. | Hour |
| HRT | Hydraulic retention time |
| HV | Heating Value |
| IRR | Internal Rate of Return |
| Kg | Kilogram |
| kWh | Kilowatt hour |
| M | Meter |
| MC | Moisture Content |
| $MJ/m^3$ | Megajoule/cubic meter |
| MJ/ml | Megajoule/milliliter |
| ml | Milliliter |
| MW | Megawatt |
| $N_2$ | Nitrogen |
| NPV | Net Present Value |
| O & M cost | Operation and Maintenance cost |
| $O_2$ | Oxygen |
| PB | Payback time |
| pH | Acidity degree value |
| PJ | Petajoules |
| R | Rand, South Africa currency |
| TS | Total solids |
| VFA | Volatile fatty acids |
| VS | Volatile solids |

# Chapter 1 – Introduction

## 1.1 Background

In recent years, there is an increase in the demand of broiler (chicken meat), and layer (chicken eggs) in the world. The world production of poultry meat is dominated by three countries namely the United States of America (USA), Brazil and China, producing a total of 53 % of the total poultry meat worldwide in 2011 (Davids, 2013). In South Africa, since 2001, there is a geometrical growth in the poultry industry. It is attributed to an increasing demand of poultry meat and egg production (Department of Agriculture, Forestry and Fisheries, 2012). The total South African laying flock is 23.5 million hens in 2009. Gauteng have the highest number of layer flock in South Africa, followed by KwaZulu-Natal and Western Cape provinces. Table 1 shows an estimated census of poultry birds in South Africa.

**Table 1.1: Estimated Census of Poultry birds in South Africa**

| **Estimated Poultry birds in South Africa** | | |
|---|---|---|
| Broiler GGP's[××] and GP's[×] | 400 000 | |
| Broiler parents in rearing | 3 155 300 | |
| Broiler parents in lay | 6 605 000 | |
| Broiler rearing | 98 743 000 | |
| **Total Broiler Industry** | | **108 554 300** |
| Commercial Layer GP's[×] | 300 000 | |
| Layer replacements pullets | 7 724 400 | |
| Commercial Layers | 23 285 700 | |
| **Total Layer Industry** | | **31 310 100** |
| **Total Industry** | | **139 864 400** |

**Source:** (South Africa Poultry Association, 2014) [××]Great grandparent (GGP); [×]Grandparent (GP).

In 2011, the South African poultry industry is the largest segment of the South African agricultural sector, contributing 24 % of the total agricultural production and in 2012, the total poultry production is 1.489 million tons, importation totaled 404 163 tons, and exportation is 8 135 tons (South Africa Poultry Association, 2012). The production of broiler is higher than the production of layer since the consumption of broiler meat is cheap, medically accepted due to its low cholesterol and protein value,

easy to cook, and religiously accepted. The Quick service restaurants e.g. Kentucky Fried Chicken (KFC), McDonald's, Kenny Rogers, Nando's Chickenland etc., do promote the consumption of broiler in South Africa. Many other animal consumptions e.g. Livestock, for example pork, beef etc., are religiously restricted. The beef is accepted by Hindu population for consumption while, pork is not consumed nor accepted by Muslim population. Due to the rapid development of poultry farms in South Africa, poultry waste is increasing yearly. Table 1.2 shows the estimated number of poultry farms in South Africa.

**Table 1.2: Number of Poultry farms in South Africa**

**Broiler Industry**

| Type of Broiler Farms | Number of Farms |
|---|---|
| Broiler breeder farms | 103 |
| Broiler rearing farms | 471 |
| **Total** | **574** |

| Type of Layer Farms | Number of Farms |
|---|---|
| Layer breeder farms | 16 |
| Layer rearing farms | 35 |
| Layer farms (egg producing) | 178 |
| **Total** | **230** |
| **Grand Total** | **804** |

**Source:** (South Africa Poultry Association, 2014)

Poultry manure is pure excreta from layer. poultry litter is the mixture of excreta and bedding material obtained from the broiler house. In this study, it is referred to as poultry litter/or waste or manure. The major problem facing the industry according to Jordaan, (2004) is the large-scale accumulation of poultry litter, which may pose disposal and pollution problems unless environmentally, techno-economically and other forms of waste management technologies are implemented. Presently, in many countries like India, Germany, China, the waste is used to generate biogas for heat and electricity (Lieberz, 2008; Uz Zaman, 2007; Mondal and Denich, 2010). Poultry litter have the potential to cause human and animal health problems as well as environmental and aquatic problems. Locally, South African poultry farmers utilize poultry litter as ruminant feed since it is a relatively cheap non-protein nitrogen (NPN) source. It is considered as a major source of fertilizer for crop production, and deposited for landfilling (Ruffini, 2013; Gerber, et al., 2007; Jingura, et al., 2009). The nitrate from the waste is deposited in the environment and occupies the waters and therefore,

greenhouse gas is emitted into the environment and to treat poultry litter for human advantage, anaerobic digestion is required. It will result in the reduction of nitrogen pollution through the nitrification/denitrification process, and biogas (energy) is generated. In biogas technology, biomethane (biogas), a renewable energy source is produced by anaerobic digestion of organic waste. The waste is converted into biogas, which is rich in methane gas (Ali, et al., 2013; Bothi, 2007). However, biogas yield from different livestock differs depending on the organic contents of their feeds. Table 1.3 compares the organic content available in fresh manure, and treated poultry waste with those from other livestock.

**Table 1.3: Nutrient content in different type of Organic waste**

| **Fresh Manure** | **Nitrogen (N) %** | **Phosphorus ($P_2O_5$) %** | **Potassium ($K_2O$) %** | **Organic matter %** | **Moisture content %** |
|---|---|---|---|---|---|
| Cattle | 0.5 | 0.3 | 0.5 | 16.7 | 81.3 |
| Sheep | 0.9 | 0.5 | 0.8 | 30.7 | 64.8 |
| Poultry | 0.9 | 0.5 | 0.8 | 30.7 | 64.8 |

| **Treated Dried Manure** | **Nitrogen (N) %** | **Phosphorus ($P_2O_5$) %** | **Potassium ($K_2O$) %** | **Organic matter %** | **Moisture content %** |
|---|---|---|---|---|---|
| Cattle | 2.0 | 1.5 | 2.2 | 69.9 | 7.9 |
| Sheep | 1.9 | 1.4 | 2.9 | 53.9 | 11.4 |
| Poultry | 4.5 | 2.7 | 1.4 | 58.6 | 9.2 |

**Source:** (Bin Ahmad, 2010).

Poultry have a moderate organic matter content compared to cattle and sheep. It is a good source of biogas (energy) generation (Appari, 2014; Ojolo, et al., 2007; Al Seadi, et al., 2009). Biogas can be used to generate heat, electricity, and useable as vehicle fuel, if purified and upgraded. However, during the purification process, contaminants like $H_2S$, water vapor, dust particles, ammonia, chlorinated compounds, siloxanes are treated, and $CO_2$ is treated in the biogas during upgrade (Johansson, 2008; Nallamothu, et al., 2013).

### 1.2 Research Problem

When poultry waste is disposed to the environment, it emits ammonia gas, methane gas and other greenhouse gases into the environment. This causes reduction in egg production, eye irritation, respiratory problems, and reduces resistance to infection in poultry birds. In humans, it causes

respiratory diseases and, in the ecosystem, e.g., aquatic ecosystem: it enriches the water by increasing the concentration of nitrogen in the water. Which results in the eutrophication of surface water therefore, causing a decline of aquatic species (Pokharel, 2010).

The problem is mitigated in Europe by utilizing the waste for production of biogas through anaerobic digestion (Lebuhn, et al., 2014). In South Africa, the unutilized waste is exposed to the environment, therefore, remains a challenge and requires adequate management. The use of the by-products slightly reduces the unpleasant odour in the environment as well as the reduction in health problems in both human and animal, but energy cost is uncontrolled (Fontenot and Hancock, 2001; Oliveira, et al., 2012). Thus, overcoming these challenges mentioned above and augment for the cost incurred on energy, the use of anaerobic digestion (AD) is suggested as the alternative method to be used for the degradation of the waste and subsequently producing biogas. It is environmentally friendly, techno-economical, cost effective, generates income and it can be practiced without advanced skills (Stafford, et al., 2013).

In this study, AD will be utilized in the treatment of poultry waste collected from three different poultry farm sites in Kwazulu-Natal to generate biogas. A techno-economic feasibility study will be assessed to determine the technical feasibility and financial viability of using biogas energy as a source of energy in the rural area.

### 1.3 Selection of Substrate

Poultry litter or waste in this study refers to excreta, urine, sand, and other bedding materials from poultry industry in KwaZulu-Natal.

### 1.4 Aim and Objectives

The main aim of this research study is to assess energy from poultry waste in KwaZulu-Natal and enhance the process of biogas production by eliminating the impurities of the sulfur content, moisture and carbon dioxide in the biogas. The objectives are:

1. To determine the energy potential of poultry waste in the KwaZulu-Natal region
2. To increase the energy density of the biogas by the removal of moisture content, incombustible and corrosive gas.
3. To assess techno-economic feasibility of biogas generation from poultry waste.

### 1.5 Research Approach

Fresh poultry litter samples were collected from Sekela farm, Emarldene poultry farm and Parkside poultry industry in KwaZulu-Natal, South Africa. The waste is a mixture of both layer and broiler organic waste mix with bedding materials: sand, feather, sawdust and their feeds. The following was

determined before waste samples was degraded for production: Hach pH meter was used to determine the pH-value of the collected waste samples because AD organism is sensitive to the pH-value of the organic waste environment. Total solid (TS) and Volatile solid (VS) of the waste was determined because the higher the VS value than TS, the higher the biogas generated. To determine TS: the waste was dried in an oven for 24 hours at 105 $^0$C and the weight of the waste after drying was recorded as the Total solid, and for the Volatile solid, the waste was ignited for 2 hours at 550 $^0$C, the outcome was recorded. Total Kjeldahl Nitrogen (TKN) was determined using a spectrophotometer to evaluate the amount of nitrogen available for the growth of anaerobic bacteria.

1 kg of poultry litter was mixed with 3 liters (L) of water at a ratio 1:3, occupying a digester of 5 liters in capacity. The mixture was poured into a water bath with temperature regulator to regulate the temperature of the slurry to the desired temperature. Biogas generated from the different compositions of poultry waste was compared according to the various factors (temperature and time). The farm which produced the highest biogas was selected for the purification process.

The generated biogas collected was purified and upgraded by treating moist, carbon dioxide and hydrogen sulfide using silica gel, water scrubbing and steel wool respectively. The gas after purification and upgrade was composed of high percentage of methane gas which was the combustible gas. Gas chromatography was used to analyze the concentration of methane gas, carbon dioxide, and hydrogen sulfide present in the biogas.

A techno-economic feasibility was performed to investigate the use of local equipment in biogas generation in the rural areas in South Africa. It consists of: the selection of technology, and the development of an economic feasibility study based on the technology selected.

### 1.6 Rational and Significance

The study of biogas generation from poultry litter and its impurity removal will be a significant contribution to the environment. The benefits are:

i. Protecting the environment by reducing pollution, especially air and water pollution.
ii. Using an alternative source of energy (waste to energy) which is less expensive than the conventional fossil fuel (Lebuhn, et al., 2014).

### 1.7 Thesis organization

The thesis consists of five chapters. The first chapter is the introduction, and it presents a brief background to the study and the problem statement.

Chapter two presents a review of the literature relevant to the study; critically evaluating literatures on the conditions, beneficiary process that can be utilized to assess energy from poultry litter. It covers the strategies that have been adopted for the assessment of biogas from poultry waste; their short-comings and treatments required to enhance biogas production.

Chapter three presents the methodology used in this study. It gives a brief description of the equipment, set-up and procedures used for biogas generation from poultry litter in the removal of carbon dioxide, hydrogen sulfide and moisture and the techno-economic feasibility of utilization of biogas as an energy source.

In chapter four, the result and discussion are presented. The results are presented and discussed based on effects of temperature, pH, impurities/contaminates on biogas produced, hydraulic retention time for biogas production, and the efficiency of the biogas after impurity treatment.

Finally, Chapter five is the conclusion and recommendations. It summarizes the important findings from the study and gives some recommendations for further research.

# Chapter 2 - Literature Review

## 2.1 Introduction

Biogas is primarily composed of methane, and carbon dioxide gases, whereby other gases are traces (small amounts). It is produced by degradation of organic waste e.g. poultry litter by bacteria in an oxygen free environment called anaerobic digestion (Bhagat, et al., 2013). The process involves four phases (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). Each of the phases of digestion can influence biogas production or yield, if the anaerobic digestion parameters (temperature, pH-values, toxic compounds, macro and micronutrients, ammonia etc.) are not favorable for digestion (Arsova, 2010). The energy density of biogas is improved by the treatment of biogas impurities (non-combustible gas contaminates) through a process called purification and upgrade (Kapdi, et al., 2005; Alonso-Vicario, et al., 2010).

## 2.2 Poultry Litter

The litter is composed of moist and organic materials that degrade faster than feathers and bedding materials. It is a fine fraction that is made up of particles which are approximately 0.83 mm in size, brownish and have the ability to clump together when squeezed. The bedding materials are made up of small wood chips, saw dust and certain unidentified small flaky materials which takes time to degrade (Bernhart, 2007). The nutrient and energy value of poultry litter depends on the feed consumed by poultry birds. Waste from birds that consume high energy feed e.g. grain-based feed generates high volume of biogas than that, that consume roughage feed, which is composed of indigestible fibrous material (Ogejo, et al., 2009). The deposition of waste to land fill valleys have resulted to change in the environment due to methane, carbon dioxide, and nitrous oxide, which are greenhouse gases (GHG). The nitrous oxide emitted from organic waste makes human, terrestrial and aquatic animals prone to lung infections and other respiratory problem, causes a reduction of oxygen level in water bodies therefore, resulting to high mortality rate of aquatic animals.

The harmful effects of unmanaged waste (e.g. poultry waste) in the environment are inhibited by using it as feed for animals (cow, and other ruminant animals) or as bedding materials (e.g. sand, sawdust, peanut hulls et al.,) and if not inhibited, there is possibility of ammonia gas emission (Ojolo, et al., 2007; Eze and Uzodinma, 2009; Mkhabela, 2004). Ammonia gas is a major threat to the health of the birds, caretakers and to the ecosystem. It causes a reduction in egg production, eye irritation, respiratory problems and reduces resistance to infection. In human, it reacts with nitrogen and sulfur oxide in the atmosphere, forms fine particles of 2.5 μm diameter, which when inhaled along with air into the lungs, causes respiratory diseases. In the ecosystem, e.g. aquatic ecosystem: it enriches the water by increasing the amount of nitrogen in the water, which results to eutrophication of surface

water therefore, causing a decline of aquatic species (Pokharel, 2010; Nallamothu, et al., 2013). Cattle especially dairy is a major source of production of ammonia, followed by poultry bird.

The above control measures are practiced globally, e.g. in South Africa; it is commonly utilized as feed supplement for ruminants since it contains high amount of protein, vitamins and minerals (Jordaan, 2004; Van Ryssen, 2001), however, is not a permanent solution to poultry waste and its harmful effects to human and its environment. Therefore, do require further alternative management e.g. in an industrially developed country of India, China, Germany and others, the surplus waste is used as sources for renewable energy generation (Gera, et al., 2013; Gielen, et al., 2014; Gielen, et al., 2015, Mkhabela, 2004).

### 2.3 Poultry litter as an energy source

The energy value in a renewable energy is called calorific value. It is determined by measuring the heat produced by the complete combustion of a specific quantity of renewable energy. The calorific value of biogas varies depending on the impurities, temperature, pressure and water vapor content that are available in the biogas (Uz Zaman, 2007). Bernhart, (2007), reviewed that the critical value of biogas from poultry litter was 13.5 GJ/ton; and Uz Zaman, (2007), reviewed that the critical value of biogas was about 20 – 22 $MJ/m^3$. Table 2.1 shows the different calorific values of different commercial fuels and their corresponding biogas.

**Table 2.1: Heating values of commercial fuels, and its corresponding biogas**

| Fuel | Heating Value | | Biogas $M^3$ | Natural Gas $M^3$ |
|---|---|---|---|---|
| 1 $m^3$ biogas | 22.1 $MJ/m^3$ | Correspond to | 1.0 | 0.7 |
| 1 $m^3$ Natural gas | 33.5 $MJ/m^3$ | Correspond to | 1.5 | 1.0 |
| 1 $m^3$ Propane | 46.0 $MJ/m^3$ | Correspond to | 2.1 | 1.3 |
| 1 L Diesel | 36 MJ/l | Correspond to | 1.6 | 1.0 |
| 1 L kerosene | 30.5 MJ/l | Correspond to | 1.4 | 0.9 |
| 1 Kg Charcoal | 29 MJ/Kg | Correspond to | 1.3 | 0.8 |
| 1 kWh Electricity | 3.6 MJ/kWh | Correspond to | 0.2 | 0.1 |

**Source:** (Uz Zaman, 2007)

It is beneficial to use organic waste such as poultry litter as substrate to generate biogas (energy) because it has low amount of toxic (e.g. carbon monoxide (CO) emission, $So_2$ and nitrogen oxide compounds) emissions (Gielen, et al., 2015). Major countries e.g. China, Germany, India, and United Kingdom uses about 140,000 tons of poultry litter to produce 12.7 MW of power (energy) annually (Abbasi, et al., 2012; Bernhart, 2007).

## 2.4 Biogas

Biogas can be generated by anaerobic (oxygen free) digestion (AD), combustion, pyrolysis, gasification and fermentation of organic matter. In anaerobic digestion process, the disintegration of the waste by microorganisms (hydrolytic, acidogenic and methanogenic) takes weeks for biogas to be generated (Oyewole, 2010; Abouelenien, et al., 2013). Table 2.2 shows the percentage composition of gases that constitute biogas.

**Table 2.2: Composition of Biogas**

| Gases | | Content |
|---|---|---|
| Methane | ($CH_4$) | 50 – 75 % |
| Carbon dioxide | ($CO_2$) | 25 – 50 % |
| Nitrogen | ($N_2$) | 0 – 10 % |
| Hydrogen | ($H_2$) | 0 – 01 % |
| Hydrogen Sulfide | ($H_2S$) | 0 – 03 % |
| Oxygen | (O2) | 0 – 02 % |
| Calorific value | | 5.5 – 8 kWh/$m^3$ |

**Source:** (Ali, et al., 2013; De Graaf and Fendler, 2010; Muzenda, 2014)

The efficiency of the generation of methane gas depends on organic waste sources, the operational parameters (hydraulic retention time (HRT) and organic load); the anaerobic parameters (pH-values, volatile fatty acids (VFA), ammonia, macro and micronutrients, and toxic compounds), and certain factors e.g. temperature, etc. which are climate related (Verma, 2002).

## 2.5 Biogas Production

Biomass is a biological material (organic material) derived from living organism. When treated by combustion, pyrolysis, anaerobic digestion, gasification, fermentation etc., the final products include biodiesel, biochar, gas and oils, carbon monoxide and syngas. The products can be further treated to improve the quality of the products by stabilization, dewatering, upgrading and refining depending on final products (Crucible Carbon, 2008). AD is used as a waste processing technique for biomass with high nitrogen and low lignin content at low temperature ranges from (30 - 40) $^0$C for mesophilic and (50 - 60) $^0$C for thermophilic digestion. It processes a wide range of biomass and must be under variable conditions (concentration of feedstock, feed material composition, hydraulic retention time, pH value, carbon-nitrogen ratio, toxicity, agitation, air tightness, moisture content, total solid and volatile solid) which are capable in influencing the quality and volume of biogas produced (McHenry, 2009; Eriksson, 2012; Stafford, et al., 2013; Masebinu, 2015).

## 2.6 Anaerobic Digestion

Anaerobic digestion (AD) is the microbial decomposition of organic matter into methane, carbon dioxide, inorganic nutrients, compost in the absence of oxygen and in the presence of hydrogen gas and the final product of the produced gas is called biogas. The sludge from the process can be utilized as fertilizer for crop production. Methane is a major constituent of biogas, is the energy gas, can be used in place of fossil fuel and is a greenhouse gas like $CO_2$. Greenhouse gas keeps the environment habitable for living things. It regulates the energy from the sun, which can be harmful to living organism by absorbing the energy from the sun. However, when there is excess availability of greenhouse gases in the atmosphere, it can cause the environmental temperature to increase and therefore, causing health problems. Today, through industrialization, agriculture, automobile and many other natural occurrences of greenhouse gas, the greenhouse gas is increasing and is calling for concern because it can cause health problems. By anaerobic digestion: the methane gas, can be utilized as energy thereby resulting in the reduction of GHG, pathogens and odor. There are four phases of AD process as highlighted before and explained below (Arsova, 2010).

### 2.6.1 Hydrolysis

It is the first step of anaerobic digestion (AD) during which complex organic matter is degraded into smaller units (monomers). In hydrolytic process, polymers like carbohydrates, lipids, nucleic acids and proteins are converted into glucose, glycerol, purines and pyridines by hydrolytic micro-organisms (amylases, lipases, proteases, cellulases and hemicellulases) as shown below. The period of degradation of organic materials differs depending on the composition of the waste. Waste, that is composed of high percentage carbohydrate degrade within hours, protein and lipids requires days for degradation and waste with more complex structure like cellulose, lignin requires weeks to be degraded. Therefore, the hydrolysis step of polymer degradation is a step of rate-limiting step (Griffin, 2012).

$$\begin{aligned} \text{Lipids} &\xrightarrow{\text{Lipase}} \text{Fatty acids, glycerol} \\ \text{Polysaccharide} &\xrightarrow{\text{cellulose, cellobiase, xylanase, amylase}} \text{Monosaccharide} \\ \text{Proteins} &\xrightarrow{\text{Protease}} \text{Amino acids} \end{aligned} \qquad Equation\ 2.1$$

### 2.6.2 Acidogenesis

The hydrolytic products (sugars, amino acids and fatty acids) are converted by acidogenic (fermentative) bacteria into methanogenic substrates which are: volatile fatty acids, alcohols, acetate, carbon dioxide, and hydrogen. During the conversion, inhibitors like ammonia and hydrogen sulfide are produced. In a suitable AD and operational parameters: mainly acetate, carbon dioxide and hydrogen are produced and if parameters are unsuitable, alcohol and volatile fatty acids are produced (Al Seadi, et al., 2009).

2.6.3 Acetogenic phase

The products (carbon dioxide, ammonia, hydrogen, alcohols, and carbon acids) from acidogenic phase are substrates for acetogenic microorganisms. It is the formation of acetate, hydrogen and carbon dioxide by oxidation of acidogenic products under acetogenic bacteria (Pudasaini, 2010).

$$2CO_2 + 4H_2 \rightleftharpoons CH_3COOH + 2H_2O \qquad Equation\ 2.2$$

2.6.4 Methanogenic Phase

Methane ($CH_4$), which is a combustible gas, is produced by methanogenic bacteria. The bacteria convert acetic acid, hydrogen and carbon dioxide into methane, carbon dioxide and water. About 70 % of the formed methane originates from acetate, while the remaining 30 % is produced from hydrogen and carbon dioxide (Al Seadi, et al., 2009). Equation 2.3 shows the reactions:

$$\text{Acetic acid} \xrightarrow{\text{methanogenic bacteria}} \text{methane + carbon dioxide}$$
$$\text{Hydrogen + carbon dioxide} \xrightarrow{\text{methanogenic bacteria}} \text{methane + water} \qquad Equation\ 2.3$$

Methane formation phase is the slowest and critical phase compared with other phases of anaerobic digestion process. It takes (5 - 25) days for biogas generation and is influenced by the composition of feedstock, feeding rate, temperature, pH-value and other AD parameters. The changes in temperature, digester overloading and large entry of oxygen into digester can terminate methane production (Al Seadi, et al., 2009; Adekunle and Okolie, 2015).

2.6.5 Substrate for Anaerobic digestion process

Agricultural residue and by products, animal manure industry, sewage etc. are sources of substrate (feedstock) for AD process. Certain substrate generates high volume of biogas than others due to the following reasons:

- Substrate must meet the nutritional requirements of the microorganisms for various components for building new cells i.e. when the nutritional level available for the microorganisms is low, there is tendency that the organisms necessary for the degradation of substrate material will die gradually instead of re-populating.
- It must include variety of components necessary for the activity of microbial enzyme system such as trace elements and vitamins (Lebuhn, et al, 2014; Cheng and Dilger, 2009).

## 2.7 Digestion Factors

The efficiency of biogas production by AD process is dependent on several different parameters as mentioned in section 2.5. When the conditions are altered during digestion, it takes a minimum of three weeks for the microorganisms to adapt to the available new condition (Pudasaini, 2010). The suitable parameters are explained below:

### 2.7.1 Temperature

It is the most important factor that affects the production of biogas in AD process. Temperature is required by microorganism if it must survive to encourage optimum population growth of the microbial consortia. The favorable temperatures for the microorganism are Psychrophilic (below 25 $^0$C), mesophilic (25 – 45) $^0$C; usually (30 – 35) $^0$C and thermophilic (45 – 70) $^0$C; usually (50 - 55) $^0$C. Psychrophilic temperature is the slowest process of microorganism effects on AD process. Though, biogas is produced but it is not widely practice since AD process is slow at this phase. The rate of AD process is dependent on the gas production rates, bacterial growth rates and feedstock degradation. Table 2.3 compares mesophilic and thermophilic temperature in the determination of the rate of AD process (Bin Ahmad, 2010; Pudasaini, 2010). At thermophilic temperature, there is high rate of AD process which requires that the loading rate must be high, the pathogen is destroyed in the process and inhibitors (e.g. ammonia) are created which inhibits AD process for biogas formation (Abouelenien, et al., 2013; Sangeetha, et al., 2014).

**Table 2.3: Comparison of mesophilic and thermophilic anaerobic digestion**

| Process Operation | Mesophilic (30 - 42) $^0$C | Thermophilic (43 - 55) $^0$C |
|---|---|---|
| Degradation rate | Lower | Higher |
| Biogas yield | Lower | Higher |
| Hydraulic retention time | Longer | Shorter |
| Sanitation | No | Possible |
| Energy demand | Low | High |
| Temperature sensitivity | Low | High |
| Process stability | High | Low |

**Source:** (Bin Ahmad, 2010; Pudasaini, 2010)

The disadvantage of Thermophilic operating temperature is its sensitivity to temperature fluctuation of (+/-1) $^0$C and which can result to reduction in methane production. Mesophilic temperature is an accepted digestion factor because it is less sensitive to temperature fluctuations of (+/-3) $^0$C, there is

high microbial consortia and process is less expensive since no additional energy input (Abouelenien, et al., 2009; Arsova, 2010).

### 2.7.2 pH-values

It is the measure of acidity or alkalinity of the organic waste and is expressed in parts per million (ppm). All stages of AD process are sensitive to pH value of the process e.g. the methanogenic bacteria are sensitive to acidic conditions which can result to stunted growth and low methane production. The ideal pH range for methanogenesis is 6.8 – 7.2 and the optimal pH is about 7.0. In hydrolytic and acidogenetic phase: pH range is 5.5 – 6.5 and at methanogenesis phase: pH is 6.5 – 8.2 (Al Seadi, et al., 2009). According to Khalid, et al., (2011), the most favorable pH range to attain maximum biogas production is 6.5 – 7.5 which varies with the kind of substrate (Arsova, 2010). pH is dependent on volatile fatty acid (VFA) concentration, bicarbonate concentration, fraction of $CO_2$ in the digester and alkalinity of the system. The pH-value in thermophilic digester is higher than in mesophilic digestion because when carbon dioxide dissolves, it forms carbonic acid by reacting with water. The pH of digestion process can be enhanced by the presence of ammonia, which is produced during degradation of proteins, therefore, inhibiting biogas production and while Volatile Fatty Acid (VFA) decreases the pH-value of the digestion process resulting to biogas production (Al Seadi, et al., 2009; Khalid, et al., 2011).

### 2.7.3 Hydraulic retention time

Hydraulic retention time (HRT) in AD process is the time (day, hour or minute) that substrate remains in the digester for biogas production. It is calculated from the equation below:

$$HRT = V_R / V \qquad Equation\ 2.4$$

| | |
|---|---|
| HRT | hydraulic retention time (days) |
| $V_R$ | digester volume ($m^3$) |
| V | volume of substrate fed per unit time ($m^3$/day) |

In the digester, the reaction of microorganisms with the substrate increases as time progresses. The optimal retention time of substrate depends on the type of the substrate, environmental condition, temperature, total solid content and the material utilized as digester. In a mesophilic digester, the retention time required for biogas production ranges from 15 to 30 days and 12 to 14 days for thermophilic digester (Ojolo, et al., 2007). Table 2.4 shows the optimum biogas produced at a given HRT (Al Seadi, et al., 2008; Arsova, 2010).

**Table 2.4: Optimum biogas produced from different substrates at a giving HRT and at mesophilic temperature**

| Substrates | Hydraulic Retention Time (Day) | Biogas yield (ml) |
|---|---|---|
| Vegetable waste | 14 | 49 |
| Fruit waste | 12 | 40 |
| Cow dung | 14 | 63 |
| Poultry waste | 14 | 85 |
| Kitchen waste | 17 | 50 |

**Source:** (Ojolo, et al., 2007)

2.7.4 Organic load

It is referred to as loading rate and is the amount of organic waste fed per unit volume of digester capacity per day. The capacity of a giving digester is always constant and does not encourage overloading of the digester. When a digester is overloaded with substrate, it results in multiplication of the acidogenic bacteria therefore, decreasing the pH in the system. The condition do affect the methanogenesis bacteria resulting to low biogas production because of inhibitors such as fatty acids accumulating the digester.

When the digester is underfed, biogas production will be low. The construction and operation of biogas plant is based on techno-economic consideration (Al Seadi, et al., 2008; Khalid, et al., 2011; Arsova, 2010). Techno-economic feasibility of biogas production must be done before construction can be carried out to meet energy demand. According to Ojolo, et al., (2007), about 12 kg (3 kg of organic waste, and 9 kg of water) of organic slurry can be loaded into about 9 L of digester for biogas production.

2.7.5 Toxicity

The microorganisms in AD process requires a favorable condition for it to populate the digester and efficiently generate biogas. The presence of large quantity of mineral ions, heavy metals and detergents can inhibit the microorganism ecosystem.

A small quantity of mineral ions (e.g. sodium, potassium, calcium, magnesium, ammonium, and sulfur) can stimulate the growth of bacteria for biogas production and it is not toxic in such a quantity. At high concentration, it can lead to toxicity of the bacteria. The presence of small quantity of NH4 (50 – 200) mg/l enhances the growth of bacteria and if the concentration is above 1500 mg/l, it becomes toxic to the process. Heavy metals (e.g. copper, nickel, chromium, zinc, lead, etc.) can stimulate the growth of bacteria and when the concentration is high, it inhibits biogas production

(Mahanta, et al., 2005). Table 2.5 shows the concentration of metal ions and above these concentrations, it becomes toxic to the AD process.

**Table 2.5: Toxic level of various inhibitors**

| Inhibitor | Inhibiting Concentration |
|---|---|
| Sulphate | 5,000 ppm |
| Nitrate | 0.05 mg/ml |
| Common salt | 40,000 ppm |
| Copper | 100 mg/l |
| Chromium | 200 mg/l |
| Nickel | (200 - 500) mg/l |
| Sodium | (3,500 - 5,500) mg/l |
| Potassium | (2,500 - 4,500) mg/l |
| Calcium | (2,500 - 4,500) mg/l |
| Magnesium | (1,000 - 1,500) mg/l |
| Manganese | Above 1,500 mg/l |

**Source:** (Porras and Gebresenbet, 2003)

## 2.8 Anaerobic digestion technology

AD technology refers to the different technology used in producing biogas from organic waste. They can digest a continuous high volume of organic waste at a sustainable organic load rate with a short hydraulic retention time. It is grouped into different categories based on the feeding mode: continuous mode, single stage, two stage and batch mode. The AD technology is structured according to AD temperature (mesophilic or thermophilic) and the shape of the reactor (Nayono, 2009).

### 2.8.1 Batch and Continuous (single and two stage) mode feeding systems

In batch mode, the reactor is sealed after loaded with organic solid substrate for a period (hydraulic retention time), for production. The limitation of the system is the risk of blockage of the leaching process caused by clogging of the perforated floor and is improved by mixing the substrate with bulk material (e.g. wood chips) or by limiting the thickness of the fermenting wastes. It is a convenient mode of digesting organic waste on laboratory scale basis since multiple digestion can be carried out before theoretical decision can be made due to lower organic loading rates and instability in microbial populations (Nayono, 2009). In single-stage system, the four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) takes place in a single stage reactor. The challenge is that the process operates under same conditions despite differences in microorganism reaction with substrate at the different stages. The waste becomes rapidly acidified thereby inhibiting methanogenesis (biogas

production stage) because the condition is not totally favorable for production. In a two-stage reactor, two reactors are used in the process. The digester conditions in the first reactor favors hydrolysis and acidification stages of AD. It involves the breaking down of carbohydrates, lipids, nucleic acids etc., and fatty acids is released, passed to the second reactor for methanogenesis, where biogas is generated. The challenges in two-stage reactor is the decrease in biogas yield while passing the outcome from first-stage reactor to the second-stage reactor. Commercially, one-stage system is preferred since is cheap to construct and technically, biogas loss is low compared to a two-stage reactor. For example: in Europe, over 90 % of AD technology is one-stage reactor (Nayono, 2009; Khalid, et al., 2011).

### 2.8.2 Wet and Dry anaerobic digestion

Wet digestion systems are designed to process dilute organic slurry with typically < 15 % total solids using Continuous Stirred Tank Reactor. Wastes with greater than 15 % total solids: the slurry is created by adding fresh water, re-circulated process water, or organic waste with a lower total solids' percentage to the incoming waste stream (i.e. co-digestion). A Continuous Stirred Tank Reactor (CSTR) is utilized as the wet anaerobic digester reactor. The feedstock must be mixed with distilled water or co-digested with liquid waste (wastewater sludge, abattoir waste, food waste etc.) to form slurry before AD process. This allows a reduction in biogas loss because biogas inhibitors are diluted after adding water or liquid waste (Guiford, 2009; Nayono, 2009).

Dry anaerobic digestion, also referred to as high-solids or solid-state digestion, is typically used to treat organic materials with high solids content between (20 – 40) % e.g. Organic fraction of municipal solid waste and agricultural wastes. The substrate is prepared by separating inorganic material from organic material. The waste is blended for proper mixing with waste and to allow for an increased reaction from the microorganism. It is transported mechanically using pumps, pipes and sealed vessels to the various unit of operations of the reactor. A good reactor capable of digesting organic waste in dry state is a plug flow reactor. The reactor is equipped with pretreatment and materials handling systems for the organic waste digestion. The advantages of dry anaerobic digestion are: it offers less complicated pre-treatment, works best with homogenous substrate therefore, allow for easy blending of the organic waste. The disadvantages are: it encourages co-digestion and the equipment are costly to purchase, build and operate. (De Baere and Mattheeuws, 2010; Guiford, 2009; Nayono, 2009). Previously, it was widely used in biogas production and in the 20s, the wet system of digestion started to dominate the biogas industrial market and the reactor used is called plug flow reactor (Nayono, 2009).

## 2.9 Pre-Treatment of Solid waste

In March 2016, the California Energy Commission invested 3 million dollars in biogas project. The focus is to improve the anaerobic digestion project, the design, construction, and operation of AD system (Fletcher, 2016). Today, Europe dominates the global solid waste to energy market with over

45 % total revenue generated from solid waste in 2014, followed by Asia. Some of the key players in solid waste to energy market and improvement of AD are: Foster Wheeler A.G., C & G Environmental Protection Holdings Ltd., Veolia Environmental, Suez Environmental S.A., Babcock & Wilcox Co., etc. (Danny, 2016). In South Africa, the country is embracing the development and improvement from international market. For example, a meat abattoir in Kroonstad uses animal waste to produce energy for the operation of the company and many other meat abattoirs utilizes pyrolysis process for syngas generation (Mathews, 2015).

### 2.9.1 Pre-treatments for process enhancement

Organic substrate is characterized by both physical and chemical compositions, which includes total solids, volatile solids, TKN, and pH-value (Bernhart, 2007). Physically, the waste is constituted with macro-inorganic compounds such as sand, dust, etc. and many other properties which influences the particle sizes, bulk density, porosity and compressibility. Chemically, the composition of certain compounds, inhibits the process of biogas production e.g. inhibition caused by toxic levels of ammonia (protein and ammonia rich substrates), fat-rich substrates, and long chain fatty acids (LCFAs), aromatic compounds, salt etc. They influence the rate of degradation of biomass at the hydrolysis stage by retarding the process of AD. Ruminant animals (cow, cattle etc.) dung is composed of complex polymers (lignin) which limits the digestion rate of the dung (Karlsson, et al., 2014). To enhance the degradation rate and which invariably influences biogas production, organic waste must be pre-treated before hydrolysis stage (Ugwuoke, et al., 2015). This affects the potential of the digestive micro-organism in degrading solid waste. Pre-treatment methods can be biological, mechanical or physio-chemical (Nayono, 2009).

#### 2.9.1.1 Biological pre-treatment

A very good example of biological pre-treatment are aerobic pre-composting method and aerobic thermophilic sludge. Aerobic pre-composting method is whereby the organic waste is treated before composting methods degrade the waste. Examples of composting methods are hot composting, cold/slow composting, and heap composting. It helps to prevent fast acidification of the slurry during AD, which can result to inhibition of biogas yield. According to Subramani and Ponkumar (2012), was an effective and efficient pre-treatment in the conversion of organic waste to biogas. Thermophilic aerobic digestion is a biological treatment of organic waste under thermophilic temperature. At the end of the degradation of the waste, a thick, wet mud of mixture of liquid, and solid components called sludge is discharged, which is either added to waste or into the digester. The pre-treatments are biological and enhance methane yields. For example, the ECRC and Welsh WA uses aerobic thermophilic sludge digestion system in treating waste before digestion, and methane production is enhanced (Lu, et al., 2007).

2.9.1.2 Mechanical pre-treatment

The degradation of waste can be limited by the particle size of the waste and therefore, the particle size must be reduced. Mechanical pre-treatment increases the rate of enzymatic degradation, reduces viscosity in digester, and reduces the challenges from floating layers (Montgomery and Bochmann, 2014). There are different methods of mechanical pre-treatment, they are: by re-mixing or blending using machinery and by reducing the particle size of the waste. It requires the usage of shredders to cut or shred the substrate and usage of hammer or ball to reduce substrate size (Zupančič and Grilc, 2012). It was recommended that the particles must be reduced to about (1 - 2) mm for effective hydrolysis (Montgomery and Bochmann, 2014).

2.9.1.3 Chemical pre-treatment

Lignin or fiber is a complex organic polymer deposited in the cell walls of many plants making them rigid and woody. It is a major component in industrial waste, forestry, agriculture and municipalities. When ruminant animals graze on plants they digest the lignin. It is a constituent in animal waste which do limit the rate of digestion and biogas production. To pretreat waste before digestion process; alkaline chemicals such as sodium hydroxide (NaOH), or ammonium hydroxide ($NH_4OH$) or lime can be added to the waste to increase biogas production (Nayono, 2009). In Junoh, et al., (2015) study, NaOH (0.7 – 15 g/l) was utilized to enhance biogas production. It was observed that the retention time was reduced when pre-treated with NaOH.

**2.10 Economic aspects and current state application**

There are different methods required in the treatment of organic waste which include: biological method and thermal conversion technology. Thermal conversion of organic waste includes: incineration, gasification, lagoon system and utilization in a CHP (Combined Heat and Power) plant, which are not economically reliable methods of generating energy. They cause several environmental effects including greenhouse gas (GHG) emissions, water pollution, and odor, which do require to be treated (Martin-Ryals, 2012). The investment cost of assembling and operating a thermal conversion method is higher than biological method of biogas generation. Currently, anaerobic digestion is the growing method of treating organic waste and is industrially considered as the AD technology (Verma, 2002; Kosovska, 2006; Nayono, 2009).

**2.11 Total and Volatile Solids biogas potentials and Measurement**

The estimation of the amount of biogas that organic waste can generate is dependent on its mixed liquor suspended and volatile solids (VS). Total solid (TS) is the remains in a vessel after evaporation of slurry at temperature of either 103 $^0$C or 108 $^0$C in an oven. When subjected to temperature above 103 $^0$C or unto dryness, toxic pollutants are released into the environment which can affect the health of the researcher and result to threats to the environment. It is recommended that total and volatile

solids measurement must be done on vacuum evaporator, therefore, the exhaust gases can be treated (Bonmatṡ and Flotats, 2003). It includes total suspended solids, which is the portion of total solids retained by a filter; total dissolved solids, is the portion that passes through the filter. The Volatile solids (VS) is the residue of total, suspended, or dissolved solids retained after combustion at 550 $^0$C. The advantage of VS analysis is that, it gives rough estimate of the amount of organic matter present in the substrate i.e. the biogas that can be produced (Sadi, 2010; Chege, 2015).

### 2.12 Inputs and their Characteristics

A biodegradable material is used as substrates (inputs) for the digester. However, due to energy potential capacity and techno-economic feasibility of different organic waste as substrate, certain organic waste is preferable as substrate. For example, in South Africa, poultry waste is the most common organic waste in Durban and she is one of the major producer of poultry birds in South Africa. It can be used as substrate in the production of renewable energy (biogas) to meet the nation's energy demand (Department of Agriculture, Forestry and Fisheries, 2010). In India, livestock dung serves as substrate (input) for biogas plant since it is the most available waste in the country (Riek, et al., 2012). Table 2.6 shows different inputs and their gas production per kg of waste.

**Table 2.6: Biogas potential of various types of organic waste**

| Type of Input (Substrate) Kg | Biogas potential per Kg waste ($m^3$) |
|---|---|
| Cattle (cows and buffaloes) | 0.023 – 0.040 |
| Pig | 0.040 – 0.059 |
| Poultry (Chickens) | 0.065 – 0.116 |
| Human | 0.020 – 0.028 |
| Crop waste | 0.037 |
| Water hyacinth | 0.045 |

**Source:** (Porras and Gebresenbet, 2003)

Organic waste from different sources got different bio-chemical characteristics which affects the amount of biogas product. They include the following:

#### 2.12.1 Carbon-to-Nitrogen (C/N) ratio

The ratio of carbon and nitrogen (C/N) of an organic waste is an essential characteristic in the production of biogas. An organic waste with C/N ratio ranging from (3 – 10) : 1 is considered optimum for anaerobic digestion (Muzenda, 2014). When C/N ratio is higher than the optimal range,

the nitrogen ratio will be consumed by methanogenic bacterial for maturity and microbial activity. It results to incomplete reaction between carbon and nitrogen compound and therefore, production is low. When the C/N ratio is very low compared to the C/N ratio as presented on table 2.7, nitrogen will be liberated and accumulated in the form of ammonium ($NH_4$). Ammonium increases the feedstock pH-value in the digester and if higher than 8.5, it becomes toxic to methanogenic bacterial (Porras and Gebresenbet, 2003; Dobre, et al., 2014).

**Table 2.7: Organic materials and their C/N ratio**

| Raw Materials | C/N Ratio |
|---|---|
| Duck dung | 8 |
| Poultry waste | 10 or 3 - 10[1] |
| Goat dung | 12 |
| Pig dung | 18 |
| Cow dung | 24 |
| Saw dust | Above 200 |

**Source:** (Porras and Gebresenbet 2003; [1] Muzenda, 2014)

2.12.2 Dilution and consistency of inputs

The input/substrate is mixed with water to form slurry, before it is fed into the digester. It is done to allow ease of AD bacterial to disintegrate the organic material resulting in the production of optimal biogas. If the waste is dry, the quantity of water to be added must be high. If the waste is diluted, the volume of water must be mixed at ratio 1:1. When the slurry is too diluted, the solid particles will settle down into the digester, and if it is too thick, the particles will hinder the flow of biogas produced. In both cases, biogas production will be less than the optimal biogas expected to be produced. To ensure optimal biogas production: the ratio of organic waste to water must be consistent, and inorganic solid materials (e.g. stone, etc.), and other materials that will not disintegrate at a giving system temperature (e.g. feathers, fibers, etc.) must be sieved from the slurry (Porras and Gebresenbet, 2003; Dobre, et al., 2014).

2.12.3 Volatile solids (V.S)

The weight of organic solid in water or in any liquid that can be burned off on ignition of dry solids at 1020 $^0$F (550 $^0$C) is called volatile solids. The higher the volatile solid content in a unit volume of fresh organic waste, the higher the biogas production (Porras and Gebresenbet, 2003). There are other factors that determines the volume of biogas produced even when the volatile solid is high e.g. pH value, C/N ratio, Total Kjeldahl Nitrogen (TKN) etc. For example, Ali and Al-Sae'd, (2015) research work revealed that: poultry litter with volatile solid (VS) of 87.8 % produced higher biogas than cow dung with VS of 93 % due to its C/N ratio and pH value.

2.12.4 Total Kjeldahl Nitrogen (TKN)

TKN is the organic nitrogen content of poultry waste and if it is high, the C/N ratio is high. It encourages the conversion of organic nitrogen to ammonium therefore, introducing inhibitors in the reactor that can reduce biogas production (Çoban, et al., 2014).

## 2.13 Enhancement of Biogas Energy

The energy gas from a produced biogas (raw biogas) are methane and hydrogen gas. Methane gas is of significant amount compared to hydrogen gas. It is considered as a dependable energy gas in a produced biogas. The presence of non-energy gases reduces its energy performance and to improve its performance, the energy density (amount of energy stored in biogas system per unit volume or mass) of the biogas must be enhanced by the removal of non-energy gases through purification and upgrade of biogas. Table 2.8 illustrates the rate of purified gas to heat up a compound (e.g. water) is lower compared to raw biogas.

**Table 2.8: Time for boiling 500 ml of water ($H_20$)**

| Energy Source | Time (minutes) for boiling 500 ml of water |
|---|---|
| Raw Biogas | 5.62 ± 0.02 |
| Purified Biogas | 4.54 ± 0.03 |

**Source:** (Nallamothu, et al., 2013)

## 2.14 Purification and Upgrade

Water vapor, dust, $H_2S$, $CO_2$, siloxanes, hydrocarbons, $NH_3$, oxygen and air, chloride and fluoride ions are impurities or contaminants in biogas (Ryckebosch, et al., 2011). To optimize the energy density of biogas; it must be purified and upgraded. Purification is the removal of contaminants from the gas stream while Upgrade is the improvement of the energy content or critical value by the removal of carbon dioxide ($CO_2$) (Shah, 2015).

2.14.1 Hydrogen sulfide ($H_2S$)

There is hydrogen sulfide in organic material. When waste is digested, the biogas produced is composed of $H_2S$ and sulfur oxides ($SO_2$ and $SO_3$). Sulfur oxide is more toxic than $H_2S$ and causes corrosion with water. It is corrosive on digester metallic parts, compressor and gas storage tanks. The reactivity increases as concentration, pressure, temperature and availability of moist increases. There are two general techniques applied in the treatment of $H_2S$ from biogas:

- Liquid phase oxidation process (treatment of $H_2S$ during digestion)
- Dry oxidation process (treatment of $H_2S$ after digestion) (Kapdi, et al., 2005)

There are disadvantages in using the above techniques which influences the volume of biogas generated. Table 2.9 shows the advantages and disadvantages of different techniques used in the treatment of $H_2S$.

**Table 2.9: Advantages and disadvantages of techniques for removal of $H_2S$**

| Method | Advantages | Disadvantages |
|---|---|---|
| Biological with $O_2$/air (in digester) | Cheap cost and exploitation: low electricity and heat requirements, no extra chemicals or equipment required. | $H_2S$ concentration still high. Excess $O_2/N_2$ in biogas result to difficulty in upgrade or purification |
| $FeCl_3/FeCl_2/FeSO_4$ (in digester) | Is feasible. Electricity and heat requirements are low. Simple operation and maintenance. No air in biogas | Efficiency is low. Operation is expensive though simple. Changes in pH and temperature upset biogas production. |
| Rust steel wool impregnated wood chips or pellets | Investment is cheap | Operation is costly. Released dust can be toxic. |
| Absorption in water | Cheap when water is available $CO_2$ is removed. | Operation is expensive: high temperature and high pressure is required. Is a challenging technique. Clogging to the absorption column is possible |
| Chemical absorption NaOH, $FeCl_3$ | Electricity requirement is low. Smaller volume required, less pumping, smaller vessels and low $CH_4$ losses. | Expensive operation and cost Difficult technique. |
| Biological filter | High removal possible: > 97 %. Low operational cost | Additional $H_2S$ treatment is required. $O_2/N_2$ in biogas require additional treatment. |
| Adsorption on activated carbon | High efficiency. High purification. Low temperature required | Expensive operation. $CH_4$ losses. Extra treatment is needed to remove $H_2O$ and $O_2$. |

**Sources:** (Ryckebosch, et al., 2011)

2.14.2 Carbon dioxide ($CO_2$) scrubbing from biogas

There are different processes utilized in treatment of $CO_2$ from raw biogas. They include physical, chemical absorption, adsorption on a solid surface, membrane separation, cryogenic separation and chemical conversion.

2.14.2.1 Physical absorption

The physical absorption method is an applicable method in the scrubbing of $CO_2$ from biogas by using pressurized water as an absorbent and is the cheapest and easiest method of absorption. When the produced biogas is fed into a packed bed column from bottom, and pressurized water is sprayed from the top at low temperature, it dissolves the $CO_2$ and $H_2S$ in biogas into water and is collected at the bottom of the cylinder (tower). It is a recommended process because it can provide about 100 % pure methane, which is dependent on factors like dimensions of scrubbing tower, gas pressure, composition of raw biogas, water flow rates and purity of water utilized. The packing materials are essential because it do assist in the absorption of water and hydrogen sulfide from biogas into water (Ryckebosch, et al., 2011). It is a common practice in Sweden, France, and USA, and their outcomes shows that about 90 % of $CO_2$ can be treated after scrubbing (Nozie, 2006; Bauer, et al., 2013).

2.14.2.2 Chemical absorption

The method involves formation of reversible chemical bonds between the solute and the solvent. The chemical solvents employed is either aqueous solutions of amines, i.e. mono-, di- or tri-ethanolamine or aqueous solution of alkaline salts, i.e. sodium, potassium, and calcium hydroxides (Zhao, et al., 2010). Farooq, et al., (2012) utilized calcium hydroxide, potassium hydroxide, and sodium hydroxide to upgrade biogas generated from biogas plant in KSK campus and Table 2.10 shows the outcome.

**Table 2.10: Biogas upgrade**

| Components | Raw Biogas | NaOH | KOH | $Ca(OH)_2$ |
|---|---|---|---|---|
| $CH_4$ (%) | 58.09 | 63.85 | 62.44 | 60.77 |
| $CO_2$ (%) | 39.67 | 35.27 | 34.69 | 34.08 |
| $H_2S$ (PPM) | 100 | 37.65 | 37.24 | 56.8 |

**Source:** (Farooq, et al., 2012)

2.14.2.3 Membrane separation

Certain components of the raw biogas are transported through thin membrane (< 1 mm) while others are retained. The movement of the component in the gas mixture is driven by the difference in partial pressure over the membrane. There are two types of membrane separation techniques: the high-pressure gas separation and gas liquid adsorption technique. The former is performed in three stages,

which separates $H_2S$, and $CO_2$ from biogas and the resulted biogas is about 96 % of methane gas. The latter is new, operates at low pressure and uses micro porous hydrophobic membranes as interface between gas and liquid. The $CO_2$, and $H_2S$ is adsorbed, while the $CH_4$ is collected. In achieving a high methane quality, membrane permeability must be high, environmentally safe and operated at ambient temperature.

2.14.2.4 Chemical conversion method

Chemical conversion can be used to obtain pure methane gas and to reduce other gas components in biogas to trace levels. It is an expensive method to practice whereby, $CO_2$ and $H_2$ are catalytically converted to methane and water (Zhao, et al., 2010). Table 2.11 shows the advantages and disadvantages of using different techniques in treating $CO_2$

**Table 2.11: Advantages and disadvantages of techniques for treatment of $CO_2$**

| Method | Advantages | Disadvantages |
|---|---|---|
| Absorption with water | High efficiency (> 97 % $CH_4$), simultaneous removal of $H_2S$ when $H_2S < 300$ $cm^3$ $m^{-3}$.<br>Easy in operation. Capacity is adjustable by changing pressure or temperature<br>Regeneration possible.<br>Low $CH_4$ losses (< 2 %)<br>Tolerant for impurities | Expensive investment. Expensive operation.<br>Clogging due to bacterial growth foaming possible.<br>Low flexible toward variation of input gas |
| Absorption with Polyethylene glycol | High efficiency (> 97 % $CH_4$)<br>Simultaneous removal of organic sulphur components, $H_2S$, $NH_3$, HCN, and $H_2O$<br>Regenerative. Low $CH_4$ losses | Expensive investment<br>Expensive operation<br>Difficult in operation. Incomplete regeneration when stripping/vacuum (boiling required).<br>Reduced operation when dilution of glycol with water. |
| Chemical absorption With amines | High efficiency (> 99 % $CH_4$).<br>Cheap operation.<br>Regeneration.<br>More $CO_2$ dissolved per unit of volume<br>(compared to water)<br>Very low $CH_4$ losses (< 0.1 %). | Expensive investment.<br>Heat required for regeneration.<br>Corrosion.<br>Decomposition and poisoning of the amines by $O_2$ or other chemicals.<br>Precipitation of salts.<br>Foaming possible. |
| PSA/VSA<br>Carbon molecular sieves. Molecular sieves (zeolites) | Highly efficient (95 – 98 % $CH_4$)<br>$H_2S$ is removed | Operation is costly<br>Losses of $CH_4$ when valves is faulty |

**Source:** (Ryckebosch, et al., 2011)

2.14.3 Removal of Moist

Raw biogas is saturated with moist, the vapor quantity is dependent on temperature e.g. at 35 $^0$C, vapor is about 5 %. There are two methods utilized in the treatment of vapor in biogas, which simultaneously treat dust, and foam from biogas.

2.14.3.1 Physical drying methods (condensation)

An affordable and simplest method of treating water vapor in biogas is by refrigeration process. The refrigerator can maintain a degree temperature above the freezing point of water (0 $^0$C). When biogas is refrigerated, vapor is displaced at a degree temperature above freezing point of water. The minimum atmospheric temperature required for the process is 0.5 $^0$C and is called minimum dew point. Note: the atmospheric temperature varies according to pressure and humidity. Examples of techniques using physical separation of condensed water include:

- Demisters: whereby liquid particles are wired mesh (micro-pores, 0.5 - 2 nm)
- Cyclone separators: whereby water droplets are separated using centrifugal forces.
- Moisture traps: whereby the gas must be compressed before cooling and then later expanded to desired pressure.
- Water traps in the biogas pipe from which condensed water can be removed (Masebinu, 2015)

2.14.3.2 Chemical drying methods.

The chemical methods utilized in the treatment of vapor in biogas are: adsorption of water vapor on silica, on alumina and adsorption of vapor in triethylene glycol (TEG, $C_6H_{14}O_4$) (Chege, 2015; Thapa, 2012). Adsorption of water with hygroscopic salts is when biogas is passed on the solid hygroscopic salt, and the salt dissolves moist molecules that is present in the biogas (Petersson and Wellinger, 2009). Table 2.12 shows the advantages and disadvantages of the different techniques used in the removal of water.

**Table 2.12: Advantages and disadvantages of techniques for removal of water**

| Method | Advantages | Disadvantages |
|---|---|---|
| Condensation method<br>Demister<br>Cyclone<br>Moisture trap<br>Water traps | Higher hydrocarbon dust and oil are removed<br>Simple techniques<br>Often used as pre-treatment before other techniques | Atmospheric pressure: dew point minimum 1 $^0$C<br>Gas at higher pressure to reach lower dew point (minimal – 18 $^0$C) but freezing can occur. |
| Adsorption dryer<br>Silica<br>Aluminium | Higher removal: dew point - 10 till – 20 $^0$C<br>Low operational cost<br>Regeneration possible | More expensive investment: pressure 6 - 10 bar<br>Dust and oil need to be removed in advance |
| Absorption with glycol | High removal: dew point - 5 till - 15 $^0$C<br>Higher hydrocarbon and dust are removed<br>Not toxic or dangerous | More expensive investment: high pressure and 200 $^0$C for regeneration. |
| Absorption with hydroscopic salts | High removal efficiency<br>Not toxic or dangerous | Higher gas volumes (> 500 $m^3$/h) to be economical.<br>No regeneration |

**Source:** (Ryckebosch, et al., 2011)

### 2.15 Techno-economic Feasibility

It is the technical feasibility and financial viability of a study and is the most suitable way of characterizing the construction of biogas plants, considering low interest and low initial instalments (Al Seadi, et al., 2008). Biogas project demands high investments, and financing is one of the key elements to ensure project viability. It differs from country to country but in general, low interest long-term loans are considered because it secures the investor against inflation through re-evaluation of unpaid debts according to the inflation rate. The pay-back period is within 20 years, which refers to the period required to recoup the funds spent in an investment. The feasibility study covered the following based on the project requirement:

- Market: It covers the estimated future sales revenue of the study based on estimated sales volume and price. Which includes the biogas and the sludge after generating biogas, which can be sold as fertilizer.
- Cost of the raw material: raw material e.g. poultry waste can be purchased for the small-scale digester (fixed dome digester) in the production of biogas.
- Plant siting, location and infrastructure: It is determined based on proximity to existing infrastructure. Infrastructure can be assessed to raw materials, required equipment etc.

- Technical concept: It covers small-scale capacity, equipment sizing, storages etc. to enable the viability of the study.
- Logistics: It covers the inbound and outbound logistics and logistics planning.
- Environmental: refers to the applicable regulatory, framework and environmental impact of the study e.g. rural area is a good applicable environment for consideration.
- Investment cost, operating cost and profitability are considered (Garcia, 2014).

The family type of digester is the simplest and home used type of digester. Table 2.13 shows the standard of various family size digester, and figure 2.1 shows the diagram of a fixed dome digester.

**Table 2.13: Standard for various family size of digester**

| Factors containers | Fixed dome | Floating drum | Plastic |
|---|---|---|---|
| Gas storage (small) | Gas storage up to 20 $m^3$ (large) | Gas storage (small) | Gas storage |
| Gas pressure bar | Between 60 and 120 mbar | Up to 20 mbar | Low and up to 2 |
| Skills | High plumbing | High plumbing and Welding | Low plumbing |
| Material availability | Yes | Yes | Yes |
| Durability | < 20 years | Relative low | Medium |
| Agitation | Self-agitation by Biogas pressure | Manual steering | Manual steering |
| Sizing | (6 - 124) $m^3$ digester volume | Up to 20 $m^3$ | Up to 6 $m^3$ digester volume |
| Biogas emission | High | Medium | Medium |

**Sources:** (Kumar, et al., 2014); (Ugochukwu, 2011); (Werner, et al., 1989); (Wargert, 2009).

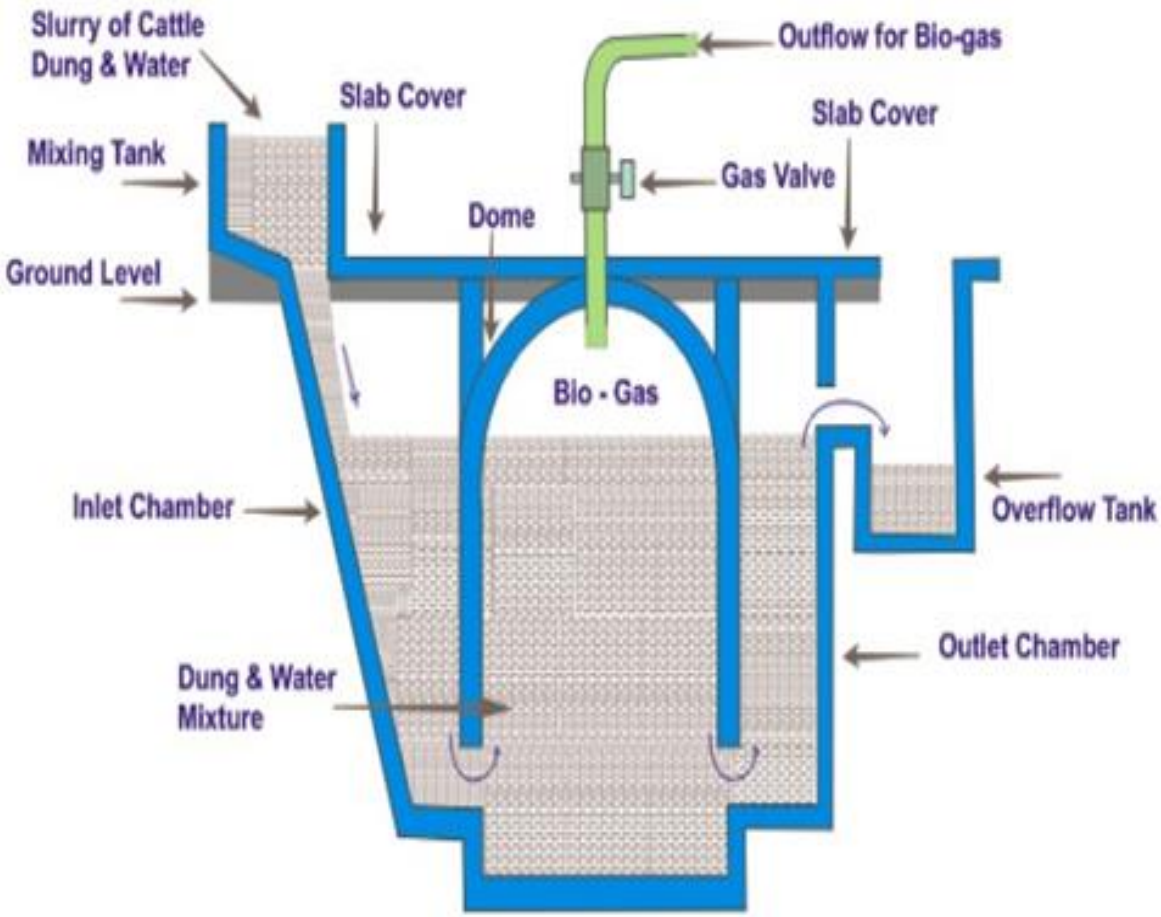



**Figure 2.1:** Fixed dome digester for poultry litter (Rauf, 2012)

### 2.16 Summary

Globally, national leaders are preoccupied with the problems of feeding the vastly increasing human population through investment into agriculture and therefore, waste from agricultural sector cannot be ruled out. It is a major environmental impact on human natural resources, water and its sources, land and human atmosphere with relation to one another and its physical environment (ecology). Organic waste contains heavy metals e.g. manganese, iron, copper, zinc and arsenic. When arsenic not properly disposed, it causes cancer in human (Thyagarajan, et al., 2013). Therefore, in South Africa, two sets of legislations, namely: The National Environmental Management Act of 1998 (NEMA): which collaborates with Environmental Conservative Act of 1989 and the National Water Act of 1998, where established to manage agricultural waste deposit, its effects to human and allowing farmers e.g. poultry farmers to adhere to them. Till today, poultry waste and its effects remain a major problem in the country (Ruffini, 2013). There is need for alternate or additional management to poultry waste.

Anaerobic digestion is the best alternative to other methods of deriving energy from poultry litter. It reduces greenhouse gas emissions, mitigates global warming, is an alternative to costly/imported

fossil fuel, waste reduction and job creation. To enhance biogas production from poultry waste, the feedstock is pretreated before digesting the feedstock, or sludge from a digested solid waste is added along with feedstock to be digested (Pudasaini, 2010; Assefa, et al., 2014). The pH-value of waste influences the growth of methanogenic microorganisms for methane production. Research works had been done: in control of AD temperature, loading rate, C/N ratio, hydraulic retention time (HRT) etc. to enhance biogas production Assefa, et al., (2014), and there is more work to be done, if pH parameters can be controlled to enhance biogas production. Biogas performance can be improved by purification and upgrade of the raw biogas.

# Chapter 3 – Methodology

## 3.1 Materials and Methods

The following equipment and resources were used in the study:

**Table 3.1: Equipment used for research**

| Make | Model | Accuracy | Precision values | Range of Instruments | Purpose of Instrument |
|---|---|---|---|---|---|
| Contherm Thermotec 2000 series | Series 2000 Oven and Incubator | Maximum performance and reliability. Assuring consistent and reputable results | Temperature control range: ambient (+ 5 – 300) $^0$C | Model 2050 - 2900 | Used to heat the poultry waste to temperatures of about 100 $^0$C, 150 $^0$C. (Series 2000 ovens and incubators – Scientific engineering, 2000). |
| (200 - 1200) $^0$ Cmuffle furnace | XD – 1200 MS muffle furnace | | Designed to heat specimen up to 1200 $^0$C maximum working temperature | There are different sizes of furnace: (200 - 1200) $^0$C, (1200 - 1400) $^0$C, (1400 - 1700) $^0$C and (1700 - 1800) $^0$C Muffle furnace | Used to ignite the waste to temperatures greater tha n 400 $^0$C. (Brother furnace, 2017) |
| Adam Equipment. Weighing balance | PGW 1502 e precision balance | | 1500 gram maximum weighing capacity | Sartorious secura 2102 1s laboratory, Sartorious cubis MSU2202S - 100 | Used to determine the weight of poultry litter samp le (Precision weighing balance, 2016) |
| OMEGA® pH meter | PHH222 Portabl epH meter | ± (0.02 PH + 2 d), ± (0.5% + 2 d) | Measurement: pH/mv/Temp: 0 - 14/-1999 to 1999 mv | PHE – 1311 to ORE - 1411 | To measure the pH of the waste before digestion an d during digestion period. (Alpha series rugged gel-filled electrodes, 2016) |
| PYREX® Graduated cylinder | Class A graduate cylinder 1000 ml | Limit of error: 5 ml. Non wetting surface. It is easy to read and clean. | Usable over wide temperature range (- 270 - 250) $^0$C | | Used to measure the volume of water displaced by the biogas generated. (Pyrex class A graduated cylinders, 2016) |
| Silica gel | | Loss on drying: < 6. Adsorption capacity at 100 % humidity: (30 - 40 ) % | Does not create any byproducts, any chemical reactions . | Particle size (mesh): 1 - 2, 3 - 4 , 3 - 8, 5 - 8, 9 - 16, and 16 - 30 | 5 - 8 mesh silica gel was used to absorb moisture from the produced biogas (White silica gel, 2016) |
| Fine steel woo l (Iron oxide) | | Capable of reducing 170 ppm of $H_2S$ to 0 ppm. Accuracy ± 0.1 ppm | | Range: Super fine, extra fine, very fine, fine, medium, medium coarse, coarse, and extra coarse steel wool | Used to absorb hydrogen sulfide present in the biogas mixture. (Magomnang, A.A.S.M and Villanueva, E.P. 2014) . |
| Shimadzu | Shimadzu's versatile GC-2014 Gas chromatography | Temperature accuracy ± 1 %. Calibration at 0.01 $^0$C increment | | GC - 2007, 2009, 2010, 2012, 2014, 2015, and 2016 series. | Used to analyse the methane, carbon dioxide, and hydrogen sulphide components in the biogas mixtu re (Capillary and packed gas chromatography GC - 2014, 2015) |
| Sigma-Aldrich | Series A - 2 gas syringe | Tend to be accurate to between 0.01 ml and 1 ml | | Capacity: 0.25 ml, 0.1 ml, 2 ml , 5 ml, 0.025 ml gas syringes | A 0.1 ml gas syringe was used for injecting biogas sample into gas chromatography. (Series A - 2 gas syringe, 2017) |

### 3.2 Digester Set-up Materials

The materials used for the construction of the biogas reactor are showed in Table 3.2

**Table 3.2: Constructed Materials**

| Part Name | Material | Specifications | Quantity | Use |
|---|---|---|---|---|
| Digester | Plastic container | 165 mm height, 220 mm diameter and 5 L volume | 9 | To store slurry during AD |
| Cork | Rubber hose | 3 cm and 5 cm (inner and outer diameter) | 2 | To prevent oxygen into digester |
| Hoses | Rubber hose | 5 mm and 6 mm (inner and outer diameter), 26 cm long | 6 | To convey biogas from digester to measuring cylinder |
| Water scrubber | Conical flask | 500 ml | 2 | Used to remove $C0_2$ from biogas collected |
| water absorbing beakers | Conical flask | 500 ml | 2 | Used to store the silica gel for absorbing water in biogas |

### 3.3 Experimental Apparatus

3.3.1 Economy Oven 80 Liter

An economy oven 80 liters, model 221 with operating temperature of (10 – 250) $^0$C was utilized to obtain the total solids (TS) of the collected samples at a temperature of 105 $^0$C. It allows error reduction and increase accuracy of the treated waste.


**Figure 3.1:** Economy oven 80 liter

3.3.2 Vacuum desiccator

After heating and igniting the samples in oven and furnace, it was taken to the desiccator (cooling equipment) for about 20 minutes for it to cool, to enable it reach ambient temperature and to prevent deliquescence (a process by which the waste absorb moisture from the surrounding air). After which it was weighed using the weighing balance because when weighed while hot, the hot sample could lengthen (or shortening) the balance pan resulting in incorrect reading, it could warm the air in contact with, and makes it rise. Therefore, bringing about an incorrect reading. Likewise, if sample was cold, the surrounding air will flow downwards, causing an error in reading.

**Figure 3.2:** Vacuum Desiccator

3.3.3 Ceramic Crucible

A high form ceramic crucible of 30 ml capacity, 37 mm height and 37 mm in diameter was used to collect feedstock (poultry waste) for TS and VS determination. It is the best for this purpose because it can be heated and ignited to temperature of about 1150 $^{0}$C. It is a high form porcelain that is glazed (coated) inside and out and thermally shock-resistant.


**Figure 3.3:** Ceramic crucible

3.3.4 Circulated laboratory water bath

The bath model IT 25 of 640 mm length, 255 mm height, 360 mm width, and approximately 12 kg weight was used. The interior is of stainless-steel tank and insulated with fiberglass. The baths was filled with water. It was used to keep the digester in the bath under a desired temperature for the study by using its circulator. The bath's circulator regulates digester temperature to the desired temperature.

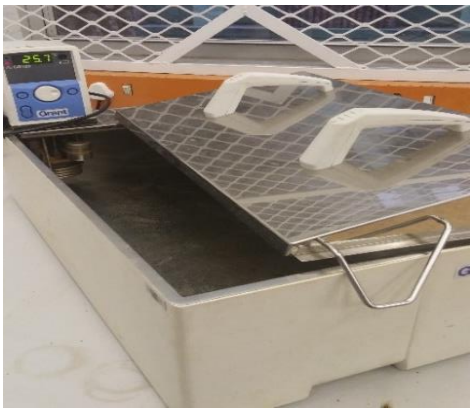


**Figure 3.4:** Circulated laboratory water bath

3.3.5 Circulator

The CPH 50 model circulator is a temperature circulator and regulator. It was attached to the bath to regulate heat within the bath to desired temperature for the digestion of the waste in the digester. It is externally coated with aluminum, the pump that circulates the temperature is made of stainless steel and is corrosion resistance. The temperature range for the circulator is approximately – 40 $^{0}$C to approximately – 100 $^{0}$C.


**Figure 3.5:** CPM 50 Circulator

### 3.4 Analytical methods

3.4.1 Determination of Total solids (TS)

The solids content of the waste samples was determined by using standard methods. Waste was placed in ceramic crucible into the drying oven, which was regulated to temperature of 105 $^0$C for 24 hours. Thereafter, it was cooled in the desiccator, and samples were weighed for TS measurement.

$$Total\ solids\ \% = \frac{W_{total} - W_{dish}}{W_{sample} - W_{dish}} \times 100 \qquad Equation\ 3.1$$

$Where$

$$W_{dish} = Weight\ of\ dish\ (mg)$$
$$W_{sample} = Weight\ of\ wet\ sample\ and\ dish\ (mg)$$
$$W_{total} = Weight\ of\ dried\ residue\ and\ dish\ (mg)$$

3.4.2 Determination of Volatile solids (VS)

The waste samples were placed in the muffle furnace for ignition at a temperature of 550 $^0$C for 2 hours to determine the volatile solids (VS) of the wastes. Equation 3.2 was used to calculate the percentage of VS available in samples.

$$Volatile\ solids\ \% = \frac{W_{total} - W_{volatile}}{W_{total} - W_{dish}} \times 100 \qquad Equation\ 3.2$$

$Where$:

$$W_{dish} = Weight\ of\ dish\ (mg)$$
$$W_{total} = Weight\ of\ dried\ residue\ and\ dish\ (mg)$$
$$W_{volatile} = Weight\ of\ residue\ and\ dish\ after\ ignition\ (mg)$$

3.4.3 pH-value

The Hach pH meter was standardized using standard buffer solutions of pH 4 and pH 7. The can bearing the waste was shaken gently after mixing with distil water, and pH was recorded after a stable reading was observed in the pH meter. The pH value of the waste samples in the batch digester was determined using pH paper by inserting it into the digester using tong.

### 3.5 Elemental analysis

Elemental analysis was conducted using 2400 CHNS/O Series ll analyser. It was used in the determination of carbon, hydrogen, nitrogen, sulphur and oxygen content in the waste. The waste samples A, B, and C (9.34 mg, 4.12 mg, and 5.14 mg) was characterised respectively using CHNS under an operating and carrier gas of oxygen and helium gas. The samples were combusted in an oxygen environment under a combustible reagent at a temperature of 800 $^0$C. The combustion products ($CO_2$, $H_2O$, $N_2$ and $SO_2$) were passed from the Combustion zone to the Gas Control Zone for characterisation. At the mixing chamber of the Gas Control Zone, gases were mixed and maintained at controlled conditions of temperature, and pressure (STP, i.e. 0 $^0$C, 760 mmHg) respectively. The product gases were passed to the Separation Zone from the mixing chamber and was measured by a Thermal Conductivity Detector (TCD) in the Detection zone of the analyser. The elemental composition values of the waste samples were expressed in percentage as showed in table 4.1 of chapter 4.

$$C_cH_hO_oN_nS_s + yH_2O \longrightarrow xCH_4 + nNH_3 + sH_2S + (c-x)CO_2 \qquad \text{Equation 3.3}$$

Where: x = 1/8(4c+h-2o-3n-2s)

### 3.6 Sample Collection, Treatments and Experimental sequence

Fresh poultry waste samples were collected from Sekela, Emarldene, and Parkside poultry industry and denoted as sample A, B, and C respectively: Figure 3.6 shows Sekela farm. The poultry waste from the Sekala was wet, mixed with sand, feed, wood, feather and the wastes were a mixture of both layer and broiler waste. They were stored in a black sealed polythene bag to conserve the moisture and microorganisms, to limit the conversion of uric acid in the waste to ammonia Ojolo, et al., (2007), and was utilized to convey the samples to Chemical Engineering Laboratory, Durban University of Technology, South Africa. At the membrane laboratory, wastes were stored in a refrigerator at 4 $^0$C until use, to prevent micro-organism from replicating, and fermenting the waste (Franceska, 2002).

Before digestion of the waste; the physio-chemical characteristics (total solids, volatile solids, TKN, and pH-value) of the wastes were determined according to standard method and were pre-treated at 100 $^0$C for 10 minutes instead of 120 $^0$C for 10 minutes, because the maximum temperature of the temperature regulator was 100 $^0$C. It was done to increase the rate of decomposition of waste for biogas production (Muzenda, et al., 2014). Five different baths were setup to achieve the objectives of the study. Each was occupied with two batch-type digesters, which were occupied with slurry (waste and water) for AD over a period called retention time. The retention time depended upon the temperature (mesophilic, and thermophilic), and the type of organic material used. However, the ideal retention time for a batch-type digester was between 15 to 30 days Rohjy, (2013), which was adopted in this study.

The first experimental procedure (Biogas production procedure) used Archimedes' principle (water displacement method) to displace water and was carried out from the 1st - 21st of July 2015, to determine the biogas available in `the wastes. The digesters were washed with distilled water and allowed to dry before it was utilized for the experiments to destroy active bacteria in the digester. Each bath was filled with distilled water, occupied with digester, filled with waste (1 kg) and water (3 L) for optimum biogas production. The second experimental setup called biogas purification and upgrade procedure was carried out during August 2015. The waste with the maximum biogas production was purified and upgraded by the treatment of vapour components using desiccant (i.e. silica gel). $CO_2$ components were treated using water scrubbing method, and a dry desulfurization system (steel wool, i.e. iron oxide) was used to treat $H_2S$ components to determine the volume of methane gas available. The raw and the purified biogas was characterised using gas chromatography (GC-2014, schimadzu) machine. The GC was fitted with TCD (Thermal Conductivity Detector) known as universal detector. According to Rodrigues, et al., (2014), is used for gas measurement except for measuring component of hydrogen sulphide, and moist gases in biogas as illustrated in Table 3.3.

**Table 3.3: Limits of Detection of Gases**

| Compounds | Limit of Detection (ppm) | | |
|---|---|---|---|
| | FID | TCD | FPD |
| Methane | 3.0 | 250 | Ns |
| Ethene | 0.5 | n.a | Ns |
| Propene | 0.5 | n.a | Ns |
| Propane | 0.5 | n.a | Ns |
| Butene | 0.5 | n.a | Ns |
| Buthane | 0.5 | n.a | Ns |
| Pentane | 0.5 | n.a | Ns |
| Carbon dioxide | 3.0 | 290 | Ns |
| Sulphur dioxide | Ns | n.a | 0.0001 |
| Nitrogen | Ns | 700 | Ns |

**Source:** (Rodrigues, et al., 2014)
FID – Flame Ionization Detector
TCD – Thermal Conductivity Detector
FPD – Flame Photometric Detector
ns – nonspecific detector
n.a – not applicable for the objective


**Figure 3.6:** Sample collection site

### 3.7 Digester Preparation for Biogas production

Each procedure comprised of a 5 L digester, 100 ml measuring cylinder, a hose and a trough. The digester was connected to 1000 ml measuring cylinder using 5 mm hose. The cylinder was inverted into a trough containing water and used as biogas collector by water displacement method. The clipped pipe on top of the digester was used as an access for the pH meter to record the daily pH-value of the slurry. The clip on the measuring cylinder was used to collect biogas from the cylinder for GC analysis. Figure 3.7 shows the schematic diagram of the experimental procedure without the bath.

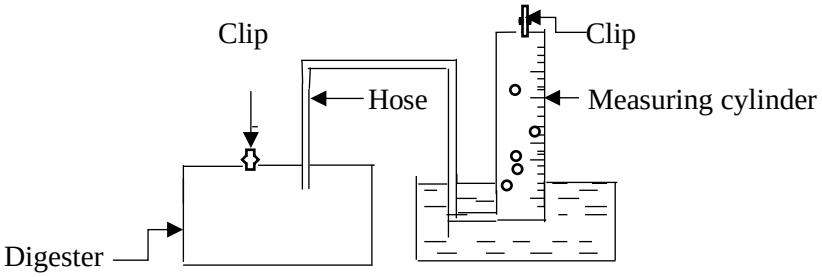



**Figure 3.7:** Schematic diagram of water displacement method

The digester was purged with liquid nitrogen for 2 minutes to displace oxygen and create anaerobic environment called asphyxiant in the digester for AD (Lloyd, et al., 2009). 1 kg of waste was weighed

from the available waste using weighing balance and was poured into the digester occupied with weighed 3 L distilled water and purged with liquid nitrogen again to flush aerobic organisms. They were mixed thoroughly: to form a slurry, to facilitate digestion for optimum biogas production. The digester was closed with digester lid, externally covered with black polythene bag, and covered with bath lid. It was done to prevent heat lost from the bath, and to exclude oxygen from the setup. It was connected to an inverted 1000 ml measuring cylinder using a hose, and the hose was to collect evolved biogas by displacement of water from the cylinder. The ends of the hose were glued to the digester and cylinder to allow airtight. The second hollow was inserted with digital pH meter tool daily to determine the daily change of pH-value of the slurry. The digester was subjected to periodic shaking to ensure thorough mixing of the substrate with the microorganisms for effective biogas production. It was kept warm at an average slurry temperature of either 30 $^0$C, 31 $^0$C, or 32 $^0$C for different digester for 21 days.

The biogas produced from the waste at each temperature (either 30 $^0$C, 31 $^0$C, or 32 $^0$C) flowed through the hose from the digester to the cylinder filled with water and water was displaced from the cylinder because biogas is not soluble in water. The volume of biogas collected was determined by the amount of water displaced from the cylinder (Archimedes' principle of floatation). The daily biogas collected was measured between 10 am to 11 am, and the pH-value was taken between 10 am and 11 am because between 10 am and 11 am the experiment was 24 hours old (a day old). Table 3.4 shows the ambient temperature and the slurry temperature. The ambient temperature represents the temperature in the bath and the slurry temperature represents the temperature in the digester. It was observed that the thermal conduction was non-equilibrium i.e. in the research, temperature in the bath was higher than the temperature in the digester probably because heat is dissipated from the digester while taking pH readings of the slurry, might be that there is heat flow with biogas as it leaves the digester to the measuring cylinder or the heat capacity of the bath might be moderate and these might have upset the degree of the temperature in the digester.

The same experimental procedure was replicated for the different samples, at each temperature, the slurry was digested for 21 days (HRT), the biogas produced, and the pH-value of the slurry was recorded daily. Each waste sample treatment for production was replicated thrice under a temperature to avoid error in determining the biogas of the waste. Figure 3.8 shows a cross-section of the experimental procedure.

**Table 3.4: Temperature ($^0$C) of the water bath to slurry**

| Ambient temperature | Slurry temperature |
|---|---|
| 35.0 | 30.0 |
| 36.0 | 31.0 |
| 37.6 | 32.0 |

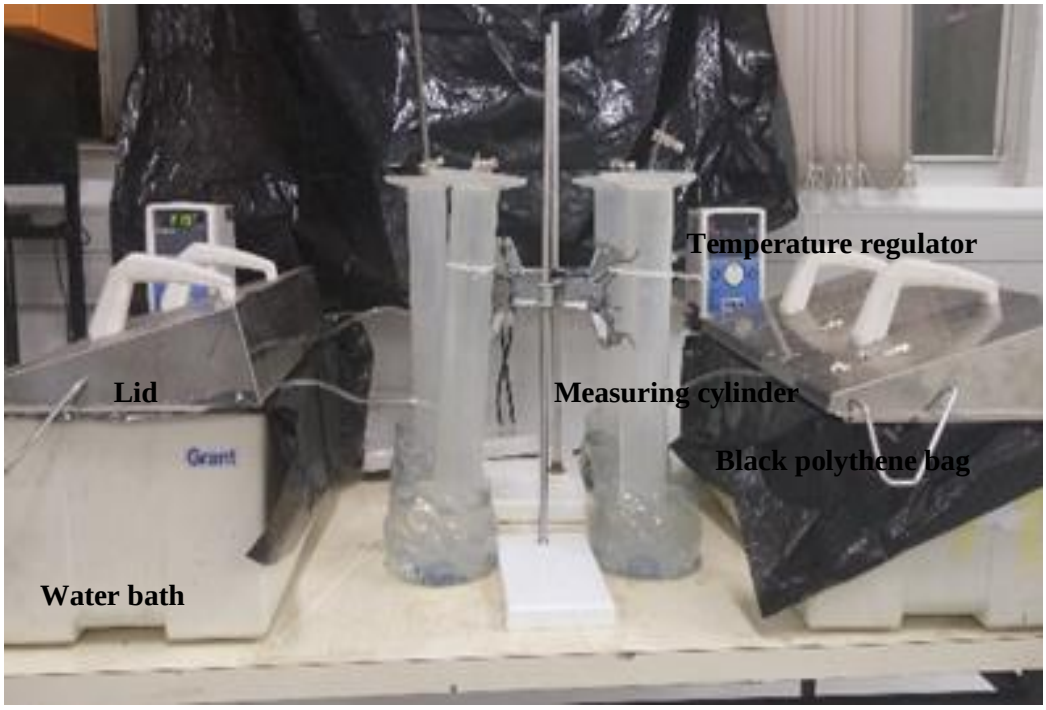



**Figure 3.8:** Cross-section of Experimental Set-up

3.7.1 Statistical Analysis of biogas production

Data collected was subjected to statistical analysis using Statistical Analysis System software in determining the effect of temperature and time on biogas collection from poultry waste. One-Way analysis of variance (ANOVA) was performed to compare variations in pH, temperature and biogas collection. Wherever significance was indicated, Duncan's multiple range tests was used to establish which treatment was significantly different.

### 3.8 Purification and Upgrade procedure

The waste that produced the highest volume of biogas from the initial experiment was used for Purification and Upgrade procedure. It consists of three sections: Dry oxidation, Water scrubbing, and Chemical drying section, and was used to treat $H_2S$, $CO_2$ and moist respectively. The purification and upgrade setup was inserted with a hose that ran from the top of the measuring cylinder to the constructed hollow cylinder called pipe or cylinder (50 mm in length). Steel wool was inserted into the pipe to trap hydrogen sulfide in biogas as it flowed into the water scrubber beaker, which was used to treat $CO_2$. It got three openings at the top and an opening by the side. The hose that ran from the pipe entered the beaker through one of the constructed holes that was on top. The second hole was inserted with ceramic funnel and was used to pass pressurized alkaline water into the beaker to trap $CO_2$ in the biogas. By the side of the beaker, there was a constructed hole called water outlet, which was used to allow outward flow of water from the beaker. The third top opening was connected to a

different beaker called Moisture Remover Beaker (MRB) using a hose. It was used to convey biogas from the water scrubber beaker to the MRB, where the moisture in the biogas was trapped. It was provided with two top openings: the first opening was to allow the biogas from scrubber into the MRB, and the last opening was for collecting biogas after removing $H_2S$, $CO_2$ and moist using 100 µL gas syringe for analysis in gas chromatography as showed in figure 3.9.

3.8.1 Experimental Procedure for Purification and Upgrade of Biogas

The setup of sample A at 32 $^0$C was used since it produced the highest amount of biogas. The raw biogas flowed through a hose attached to the top of the measuring cylinder from the first experiment unto the Biogas Purification and Upgrade sections. It flowed into the hydrogen sulfide section through a hose. The iron oxide in the section was able to trap the hydrogen sulfide components in the raw biogas: equation 3.4 showed the reaction of iron oxide with hydrogen sulfide in biogas and with oxygen. The raw biogas flowed into the water scrubbing section for upgrade. During the experiment, a continuous flow of pressurized alkaline water was passed into the water scrubber beaker. Therefore, intercepted the raw biogas from the hydrogen sulfide section, to allow the carbon dioxide components in the biogas to be dissolved in the alkaline water and allowed to flow simultaneously with the water. It left the scrubbing beaker through a water outlet on the beaker. The biogas passed through the second hose provided on the top of the beaker into a different beaker called MRB, which consists of silica gel (105 g), it absorbed the water vapor in the biogas. The biogas was collected using a 100 µL gas syringe from the MRB to the gas chromatography for characterization.

**Equation 3.4**

Iron oxide reacts with hydrogen sulphide forming iron sulphide

$2Fe_2O_3 + 6H_2S \longrightarrow 2Fe_2S_3 + 6H_2O$

When the iron sulphide is exposed to atmosphere, it reacts with oxygen to form iron oxide.

$2Fe2S3 + 3O2 \longrightarrow 2Fe_2O_3 + 6S$

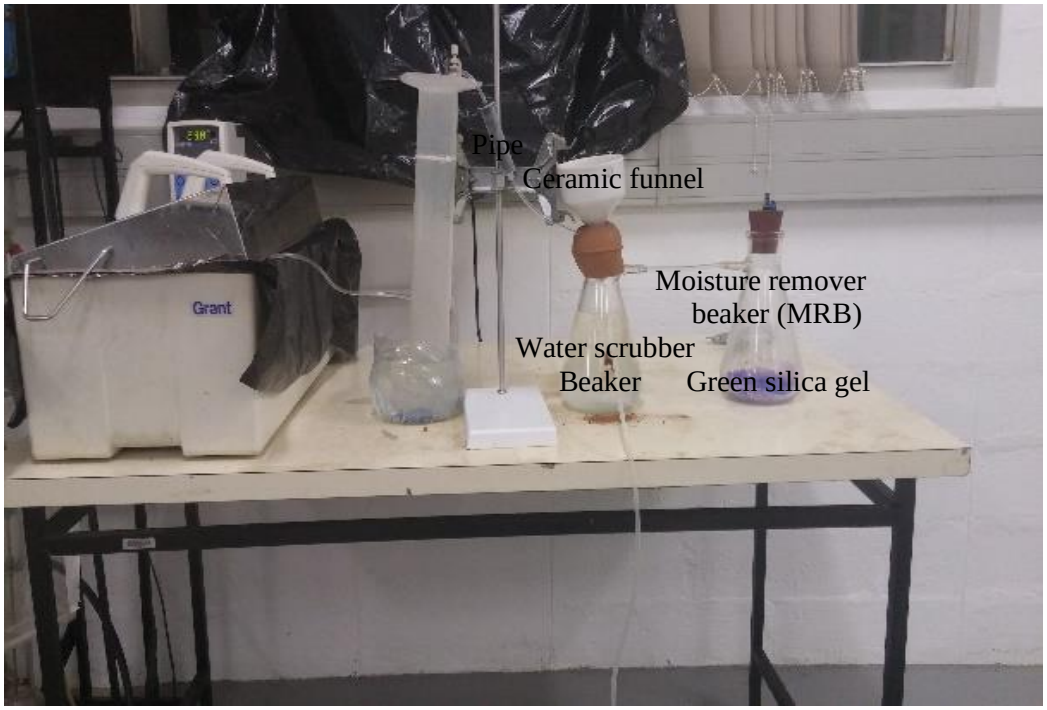



**Figure 3.9:** Biogas purification and upgrade

### 3.9 Techno-economic Feasibility analysis

It is required to do a techno-economic feasibility of biogas generation in a community where: there is no national grid electricity, the electricity is in short supply due to long hours of load shedding, firewood is used for heating or shortage of wood for heating and cooking. It will enable them to know the energy demand for the community and the cost to generate energy for domestic usage.

The feasibility study done enabled an owner:

- To make an informed investment decision regarding the construction of biogas plant.
- To know the type of digester that will be feasible in the rural area.
- To know the cost of operation and maintenance of the digester.

The study focused on a family residing in a rural area in South Africa. A family size type of digester (fixed dome) was accessed.

#### 3.9.1 Economic Analysis

Analysis was concerned on the use of biogas as alternative energy in the rural community. Energy was derived from poultry waste as feedstock. The Payback period was computed. In the study, two scenarios were assumed.

Scenario 1: was the usage of energy from South Africa national power grid.

Scenario 2: was the production of energy from poultry waste. The description, and factors of the scenarios are presented in detail in Chapter 4.

### 3.9.2 Payback time (PB)

It represents the length of time (years) to recover the investment costs.

$$PB = \frac{Total\ amount\ invested}{Estimated\ Annual\ Cash\ Flows} \qquad Equation\ 3.5$$

Income (cash inflow) was incentives from Eskom, government and sales of compost. In South Africa a ton of poultry waste is R100 (Chicken manure for sale, 2017). There is tax incentive in renewable energy generation in South Africa: (45 – 95) c per kWh is government tax incentive for generation of renewable energy Government, (2017) and R1.20 per kWh is Eskom's rebate for generating renewable energy (Creamer, 2013; De Jongh, et al., 2014).

# Chapter 4 - Results and Discussion

## 4.1 Feedstock Characteristic

Table 4.1 shows the physiochemical characteristics (TS, VS, MC, pH-value, C:N ratio and TKN) of the waste samples. The TS of sample B is higher than that of sample A and C, which probably indicates a high percentage of suspended solids in sample B therefore, encouraged a low volume of biogas compared to sample A and C. This agrees with Eze and Uzodinma, (2009) report, that high volume of biogas was produced from waste with less amount of TS. The percentage of volatile solid from sample B was lower while compared to sample A and C. It probably attributes to the roughage diet that was fed to the chicken. Therefore, sample A and C, might produce high biogas compare to waste B and agreed with Chege, (2015) report, that waste with high percentage of volatile solids are observed from grained based diet which constituted carbohydrate, protein and fats necessary for organic matter that encourage high biogas production. The moisture content of the samples are 32 %, 27 % and 32 % for waste sample A, B and C respectively. It probably indicated that waste A and C with high MC % will be efficiently degraded by the available moisture content and ready for anaerobic reaction as observed in Eze and Uzodinma (2009) study: that waste with higher MC produces a higher biogas than waste with low MC. The pH-values of the waste samples were less acidic because the pH-values are slightly 7. This would probably encourage irregular production because acidogenetic and hydrolytic phase would not be active during digestion and agrees with Al Seadi, et al., (2009). From Table 4.1, the C:N ratio of the samples shows that, there will be mild production of biogas from the samples. Waste sample A will probably produce more biogas than that of waste sample B and C because it has a high value of C:N ratio. The C:N ratio agrees with the C:N ratio range indicated by Muzenda, (2014), which stated that high biogas production was expected from C/N ratio of (3 - 10) : 1. Table 4.1 also indicates that the TKN of the samples was sustainable for high biogas production since probably low inhibitors will be produced from waste samples during AD as indicated by Çoban, et al., (2014): that at high TKN values, organic nitrogen from TKN was converted to ammonia to inhibit biogas production. It is also seen that, waste A will probably produce higher biogas compare to waste B and C.

**Table 4.1: Poultry waste characteristics in weight %**

| Parameter | Poultry waste A | Poultry waste B | Poultry waste C |
|---|---|---|---|
| **Total Solids (%)** | 68.0 | 73.0 | 68.0 |
| **Volatile Solids (%)** | 20.0 | 18.3 | 20.0 |
| **Moisture content (%)** | 32.0 | 27.0 | 32.0 |

| | | | |
|---|---|---|---|
| **Ash (%)** | 12.0 | 8.7 | 12.0 |
| **pH-value** | 6.9 | 6.9 | 6.8 |
| **TKN (g/kg)** | 2.2 | 2.4 | 2.3 |
| **Carbon (%)** | 19.7 | 13.6 | 15.6 |
| **Hydrogen (%)** | 5.1 | 8.7 | 7.2 |
| **Nitrogen (%)** | 4.5 | 4.4 | 4.4 |
| **Sulfur (%)** | 1.4 | 2.3 | 1.2 |
| **C/N Ratio** | 5.1 | 4.1 | 4:1 |

The quantity of biogas produced from organic waste (e.g. poultry waste) was influenced by the loss of biogas and presence of inhibiting substances e.g. stones, straw (long particles), feather, wood shavings etc. Which can probably cause scum layer in the digester slurry and result to low biogas collection. Figure 4.1 (a - c) – 4.3 (a - c) below illustrates the influence of inhibitors and unfavorable parameters in biogas production. In the absence of inhibitors, the actual production from volatile solids of the waste is called biogas yield. Figure 4.4 (a - c) – 4.5 (a - c) shows the actual biogas yield if digestion was not interrupted by inhibiting substances therefore, quantity of biogas yield is always higher than biogas produced.

**4.2 Biogas generation**

Figure 4.1 (a - c) shows biogas production from poultry waste A, B, and C at a constant average temperature of 30 $^0$C, 31 $^0$C or 32 $^0$C for 21 days respectively. The daily quantity of biogas produced was approximately (± 1.0 – ± 5.0) ml/day different from the former day. The Figures shows, that useable energy was not produced from the waste samples for the first 2 days. It probably indicates that, methanogenic bacteria is developed during this time since no effluent from existing digester was placed in the new digester (Prasad, 2012). On the 3$^{rd}$ day, production started from the three different wastes at the available different temperatures. This could be due to the fact that there is a fast degradation of waste by AD micro-organisms because the wastes were pre-treated before digestion. The results agrees with Ugwuoke, at al., (2015), that the pretreatment of waste at high temperature promoted the rate and volume of biogas produced. If the waste was not pretreated, biochemical reaction of the slurry could take place after 3 days because at mesophilic temperatures biogas production is slow (Prasad, 2012). At constant temperature, the heat in the digester continued to increase with time resulting to endothermic temperature, resulting in the waste increasing its rate of

degradation with time. Optimum production of biogas is observed on the 14th and 15th day as also indicated with Oyewole, (2010), whereby an optimum production was observed on the 14th day.

Figure 4.1 (a and c), the general trend observed, shows that waste A produced the highest biogas when compared to waste B and C. This is probably due to physio-chemical characteristics of the waste. It has been suggested that waste with low total solids, high volatile solids produces high quantity of biogas (Al Seadi, et al., 2009). However, Figure 4.1b shows waste C producing the highest biogas at 31 $^0$C. It is attributed to low production of inhibitors at 31 $^0$C for waste C during digestion compared to waste A and B at 30 $^0$C, 31 $^0$C and 32 $^0$C since at mesophilic temperature, digestion is less sensitive to temperature. Therefore, low inhibitors are produced (Bin Ahmad 2010).

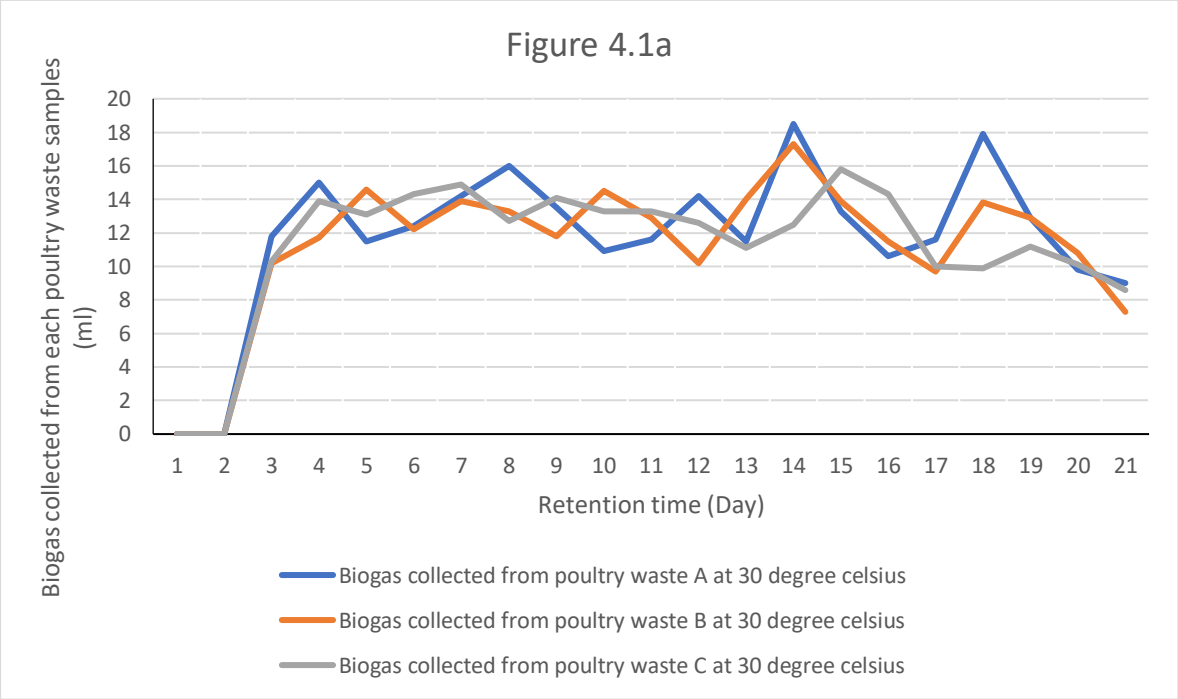



**Figure 4.1a:** Biogas collection with time for poultry waste A, B and C at an average temperature of 30 $^0$C

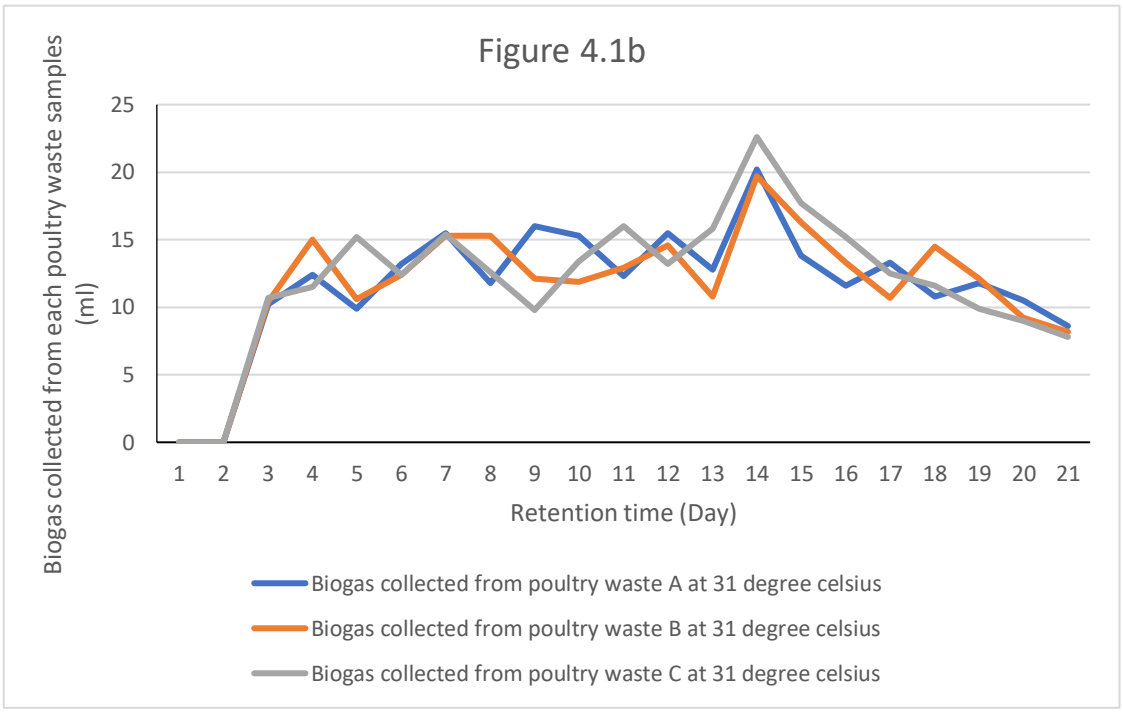



**Figure 4.1b:** Biogas collection with time for poultry waste A, B, and C at an average temperature of 31 $^{0}$C

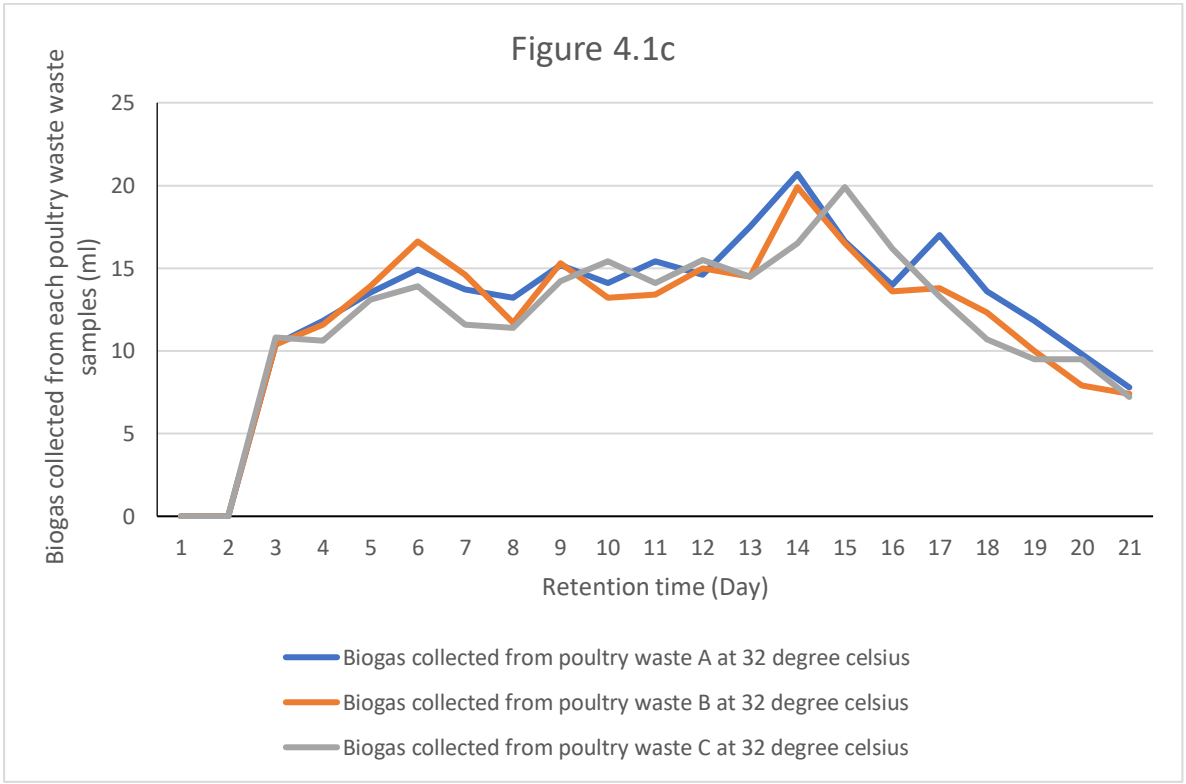



**Figure 4.1c:** Biogas collection with time for sample A, B, and C at an average temperature of 32 $^{0}$C

Figure 4.2 (a - c) shows production of biogas from a poultry waste site (poultry waste A or B or C) at varied temperature. Biogas production was not steady throughout the retention time. The production continued to fluctuate until an optimum biogas was observed on the 14$^{th}$ day. In Figure 4.2 (a and b): high biogas production was observed for waste A and B at temperature of 32 $^{0}$C. This may be due to degradation of high amount of lignin and cellulose at high temperature of 32 $^{0}$C. In figure 4.2c: waste sample C at 31 $^{0}$C generated a high quantity of biogas compared to production from waste sample C at 30 $^{0}$C and 32 $^{0}$C. The result showed a slight influence of temperature on high biogas production probably because the waste was thoroughly mixed with water which might have affected production at high temperature of 32 $^{0}$C.

Figure 4.2 (a and b) results agreed with Abouelenien et. al., (2009) report, that biogas production was favored with an increased temperature and as temperature drops, so the rate of biogas production declines.

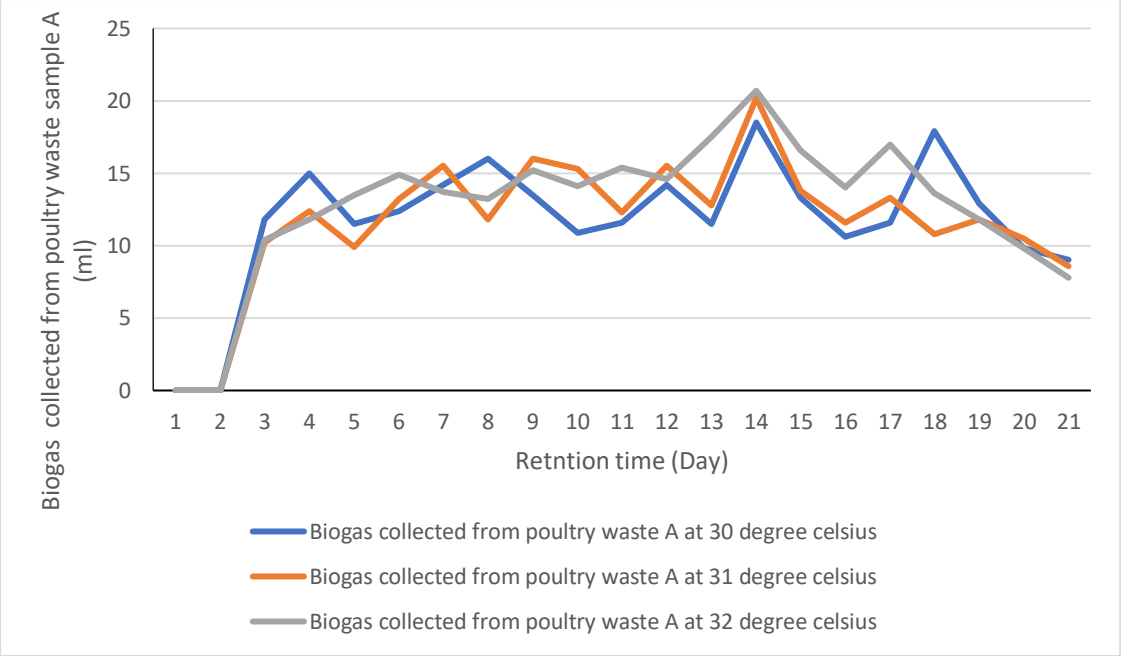



Figure 4.2a: Comparing biogas collected from poultry waste sample A with time at 30 $^{0}$C, 31 $^{0}$C, and 32 $^{0}$C

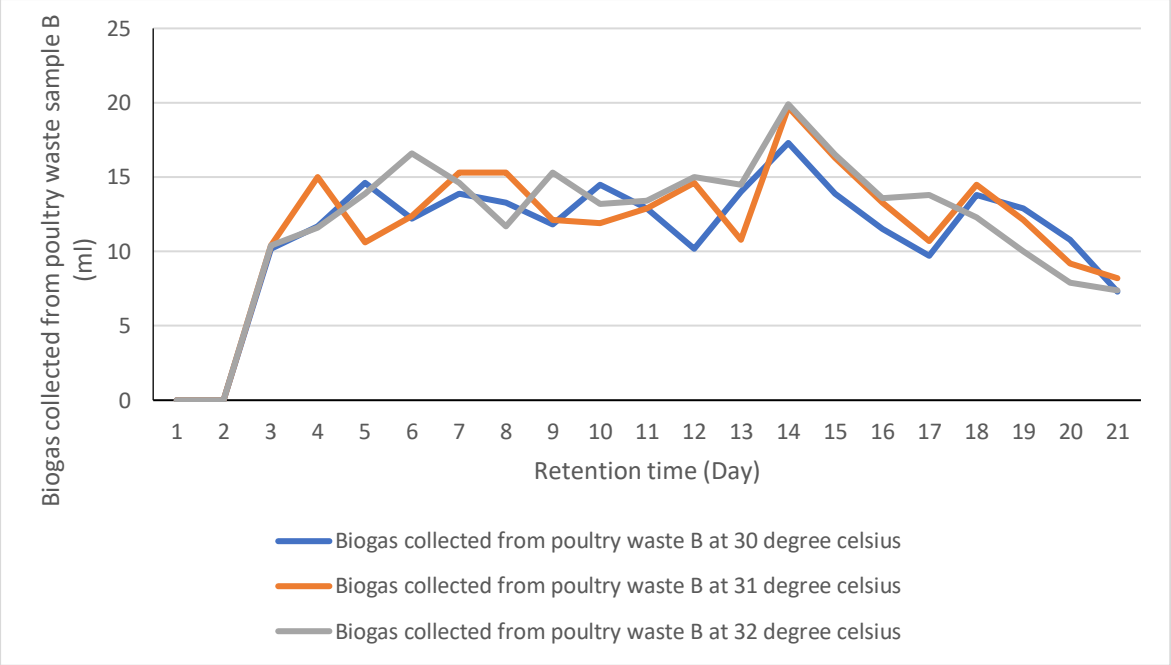



Figure 4.2b: Comparing biogas collected from poultry waste sample B with time at 30 $^0$C, 31 $^0$C, and 32 $^0$C

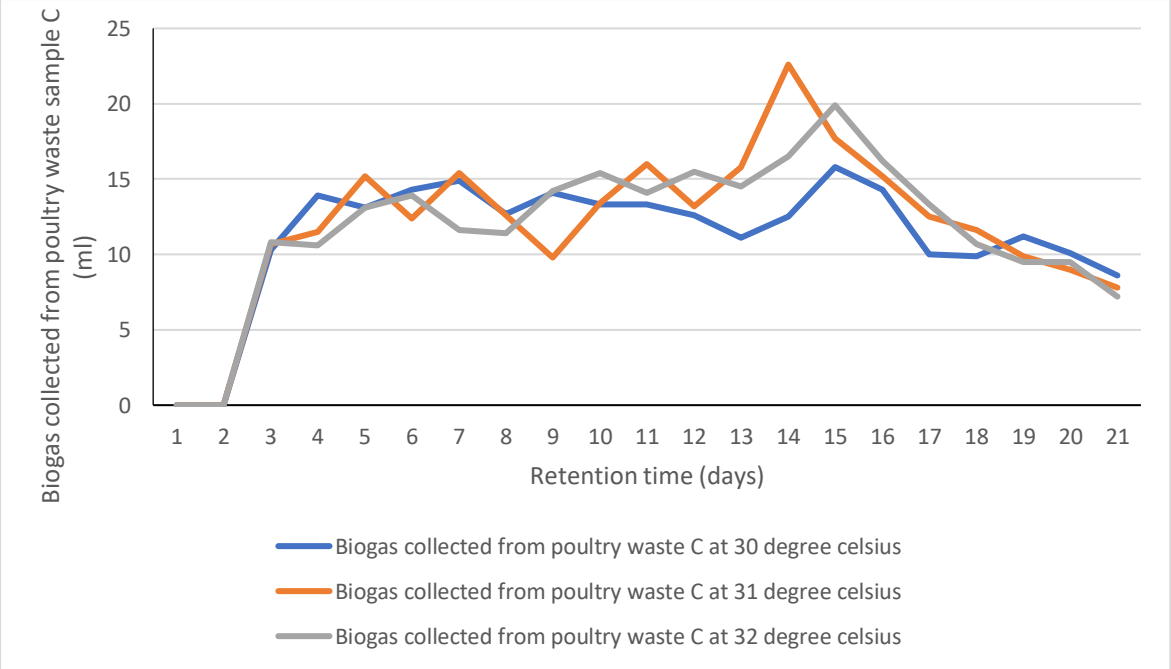



Figure 4.2c: Comparing biogas collected from poultry waste sample C with time at 30 $^0$C, 31 $^0$C, and 32 $^0$C

### 4.3 Cumulative Biogas produced

Figure 4.3 (a - c) shows the cumulative biogas produced from waste sample A, B and C at a constant temperature. Figure 4.3a shows that, the cumulative biogas produced from poultry waste sample A, B and C was 246.2 ml, 236.5 ml, and 236.0 ml respectively at an average slurry temperature of 30 $^0$C over a period of 21 days. Waste A produced the highest volume of biogas compared to waste B and C. From Figure 4.3b, the biogas collected is shown to be 245.5 ml, 245.3 ml, and 252.3 ml from poultry waste A, B and C at constant temperature of 31 $^0$C. Waste C produced the highest volume of energy compared to waste A, and B. Figure 4.3c shows that, the biogas collected is 265.6 ml, 251.6 ml and 247.9 ml from waste A, B, and C at an average temperature of 32 $^0$C respectively. Waste A produced the highest quantity of biogas compared to waste B and C.

The outcomes may be due to the waste samples physio-chemical properties as reported by Chege, (2015) except for Figure 4.3b. This is probably, because the waste was thoroughly mixed manually than waste A, which physio-chemical characteristics favors high biogas production than waste B and C.

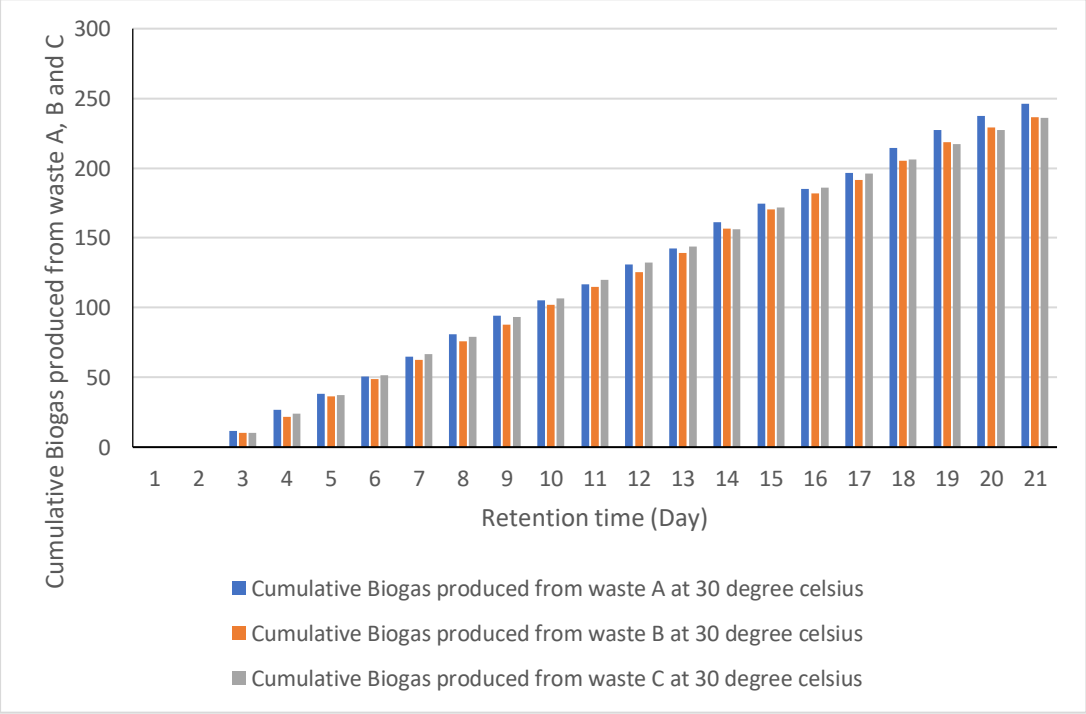



**Figure 4.3a:** Cumulative Biogas produced with time for poultry waste A, B and C at an average temperature of 30 $^0$C

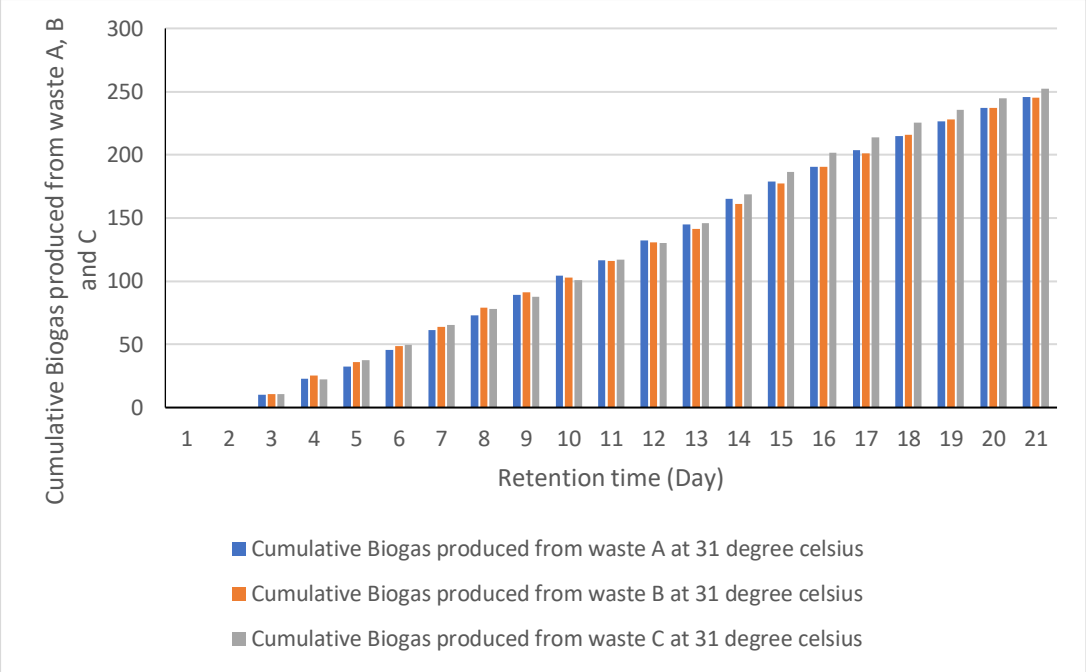



**Figure 4.3b:** Cumulative Biogas produced with time for poultry waste A, B and C at an average temperature of 31 $^{0}$C

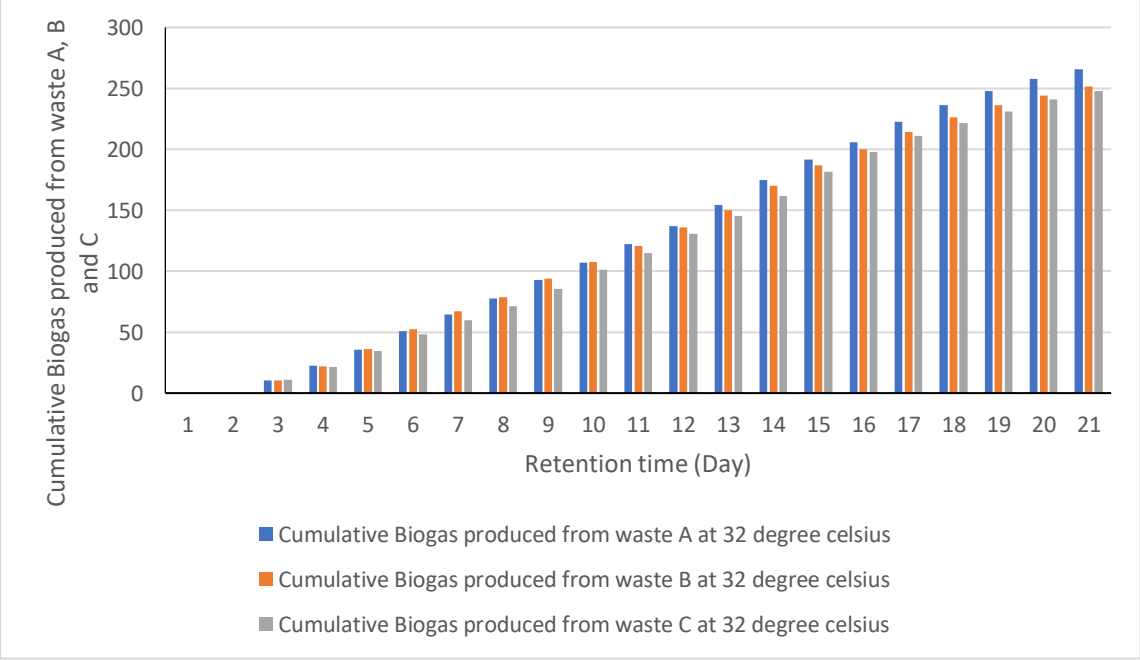



**Figure 4.3c:** Cumulative Biogas produced with time for poultry waste A, B and C at an average temperature of 32 $^{0}$C

### 4.4 Biogas Yield

Figure 4.4 (a - c) represents the biogas yield from waste A, B and C at constant temperature for 21 days. The graphs show unsteady yield with time until on the 14$^{th}$ day when optimum yield was observed. From figure 4.4a, the yield in waste A (390.8 ml/g VS) was higher compare to yield from waste B (347.8 ml/g VS) and C (337.1 ml/g VS) at 30 $^{0}$C respectively. Figure 4.4b shows higher biogas yield from waste A (389.7 ml/g VS) compared to yield from waste B (360.9 ml/g VS) and C (360.5 ml/g VS) at 31 $^{0}$C respectively. Figure 4.4c, shows yield of 421.6 ml/g VS, 370.1 ml/g VS and 349.1 ml/g VS respectively with waste sample A generated more yield than waste B and C.

The results from Figure 4.4 (a - c) is probably due: to mild loss of biogas during digestion, to the waste sample having higher VS and higher carbon content. It agreed with Ojolo, et al., (2007) study, that yield was favored with high VS, and lesser loss of biogas during reaction in digester. Figure 4.4 (a - c) shows that waste C produced the lowest, probably due to high loss of biogas during digestion and waste A produced the highest, probably due to low loss of biogas in the digester, high VS and carbon content.

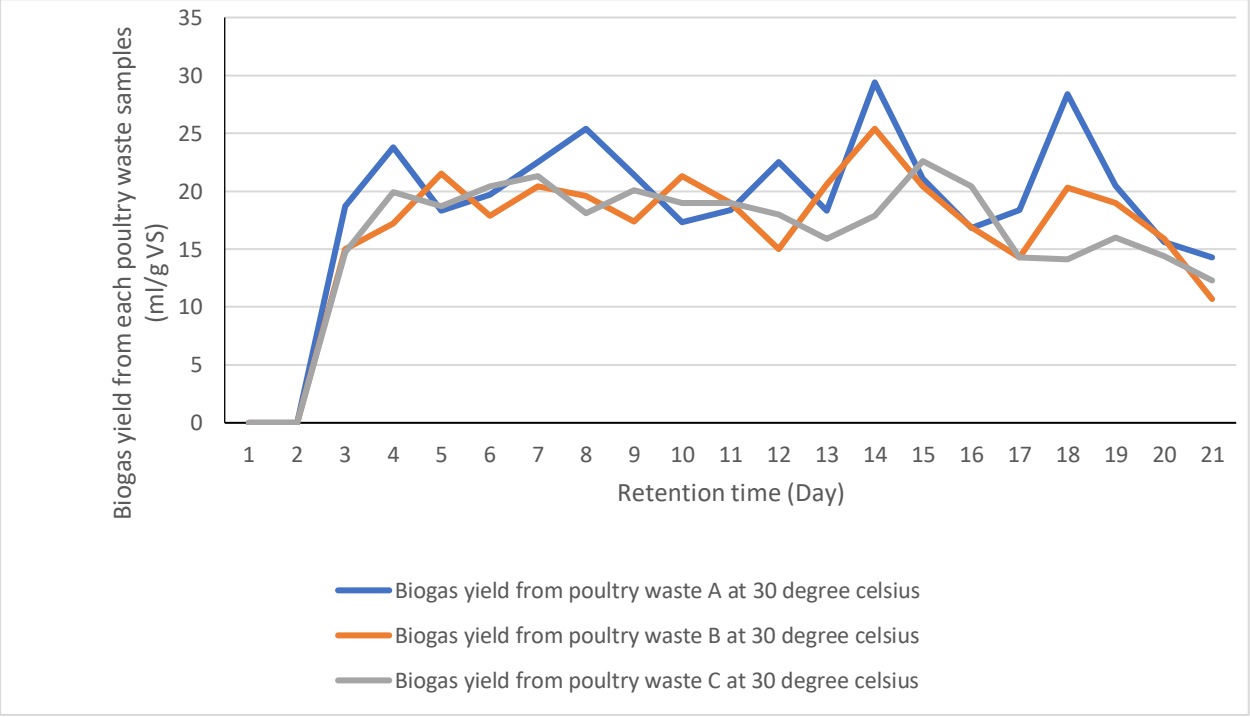



**Figure 4.4a:** Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 30 $^{0}$C

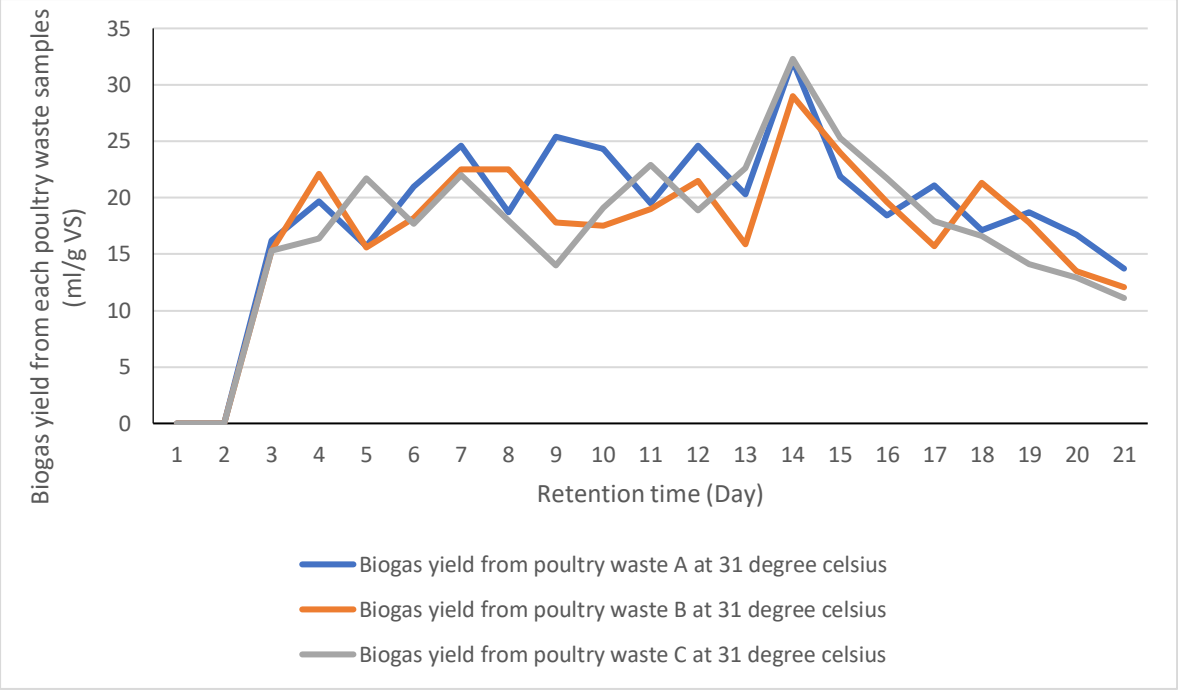



**Figure 4.4b:** Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 31 $^{0}$C

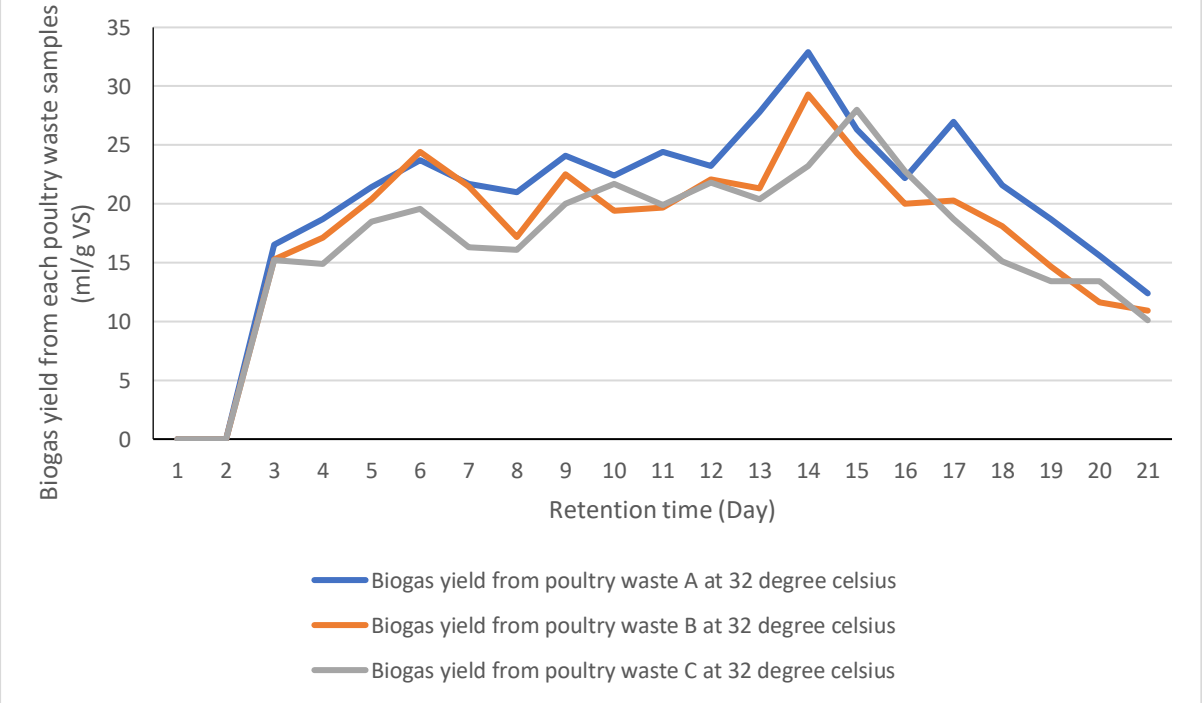



**Figure 4.4c:** Biogas yield from poultry waste A, B, and C with retention time at an average temperature of 32 $^{0}$C

Figure 4.5 (a - c) shows biogas yield of waste sample from a given poultry site (poultry waste A, B or C) under variable temperature of 30 $^0$C, 31 $^0$C and 32 $^0$C. Figure 4.5a shows the yield produced from waste A are: 390.8 ml/g VS at 30 $^0$C, 389.7 ml/g VS at 31 $^0$C and 421.6 ml/g VS at 32 $^0$C. The waste sample A at 32 $^0$C produced the highest yield. In figure 4.5b, yields are 347.8 ml/g VS at 30 $^0$C, 360.9 ml/g VS at 31 $^0$C and 370.1 ml/g VS at 32 $^0$C for waste sample B. Maximum yield was observed from waste sample B at 32 $^0$C. Figure 4.5c shows yields of: 337.1 ml/g VS at 30 $^0$C; 360.5 ml/g VS at 31 $^0$C and 349.1 ml/g VS at 32 $^0$C for waste C. At 31 $^0$C, optimum yield was observed for waste sample C. The results from Figure 4.5 (a and b) is probably due to the high temperature in the digester. It agrees with Arsova, (2010) study, that yield was favored with high temperature. In Figure 4.5c, the influence of temperature on yield was different. It probably might be that the inhibitors were sensitive to heat that it could reduce the yield from waste C at 32 $^0$C and the result agreed with Bin Ahmad (2010), that at mesophilic temperature (25 – 45) $^0$C, yield was less sensitive to temperature.

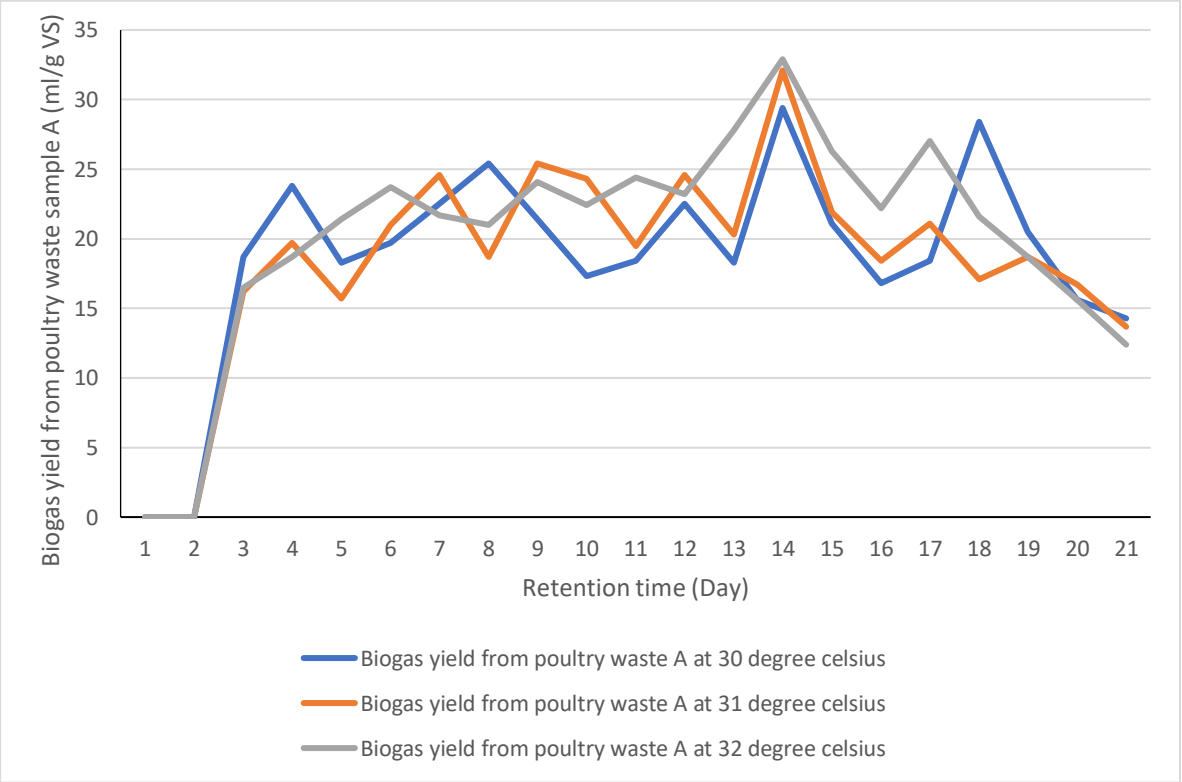



**Figure 4.5a:** Comparing biogas yield from poultry waste A at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time

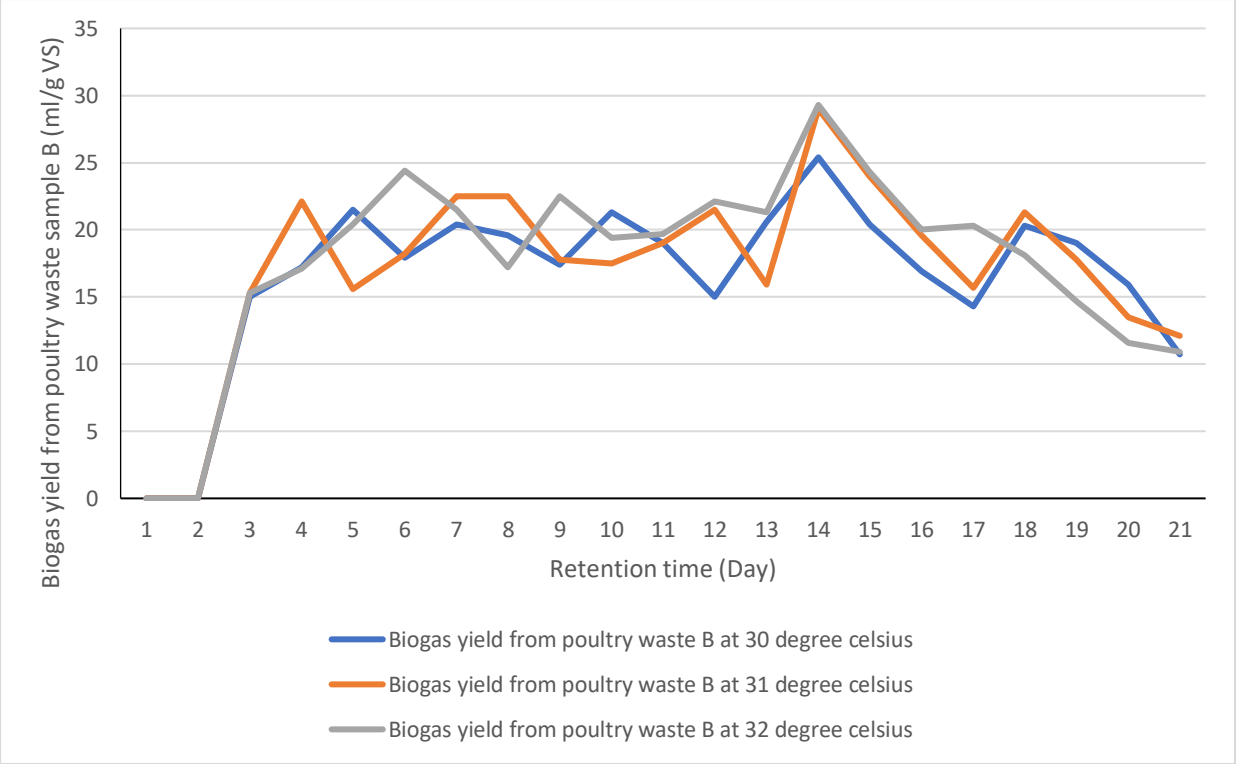



**Figure 4.5b:** Comparing biogas yield from poultry waste B at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time

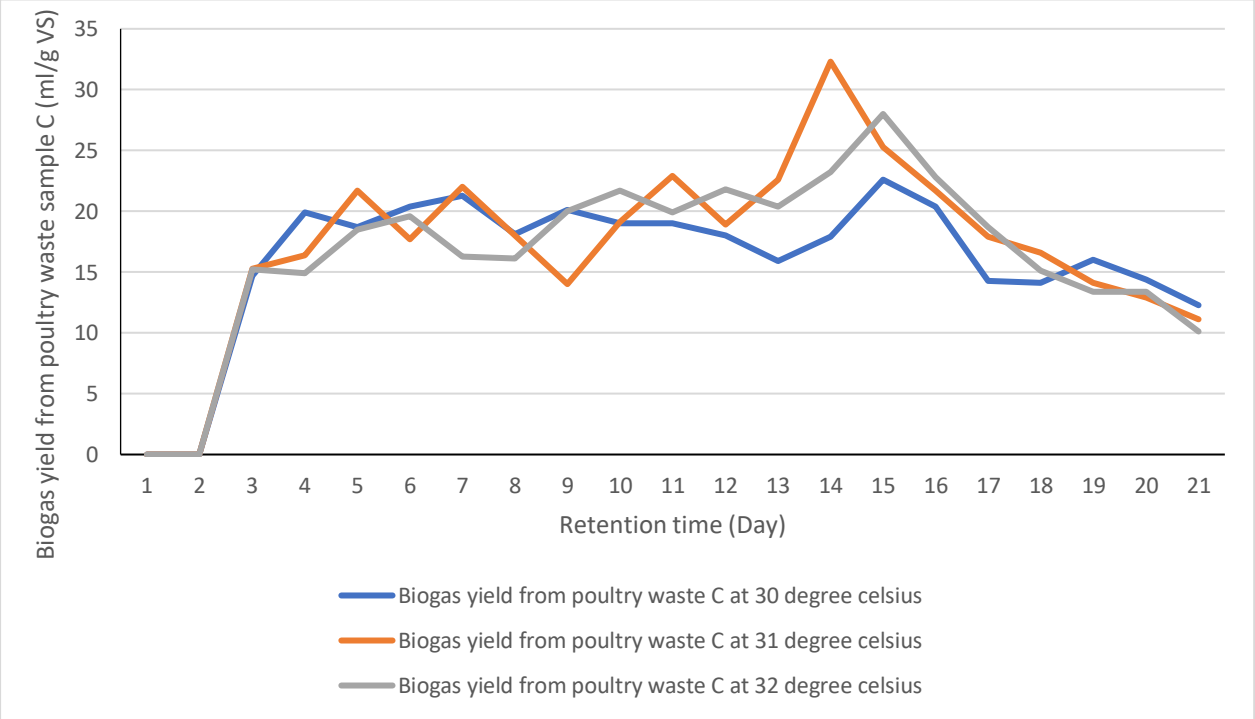



**Figure 4.5c:** Comparing biogas yield from poultry waste C at 30 $^0$C, 31 $^0$C, and 32 $^0$C with time

### 4.5 Effect of pH on Biogas production

Effect of pH in the study refers to the outcome of pH during biogas production in the digester with time. Figure 4.6 (a - c) shows the pH result during biogas production with time. Figure 4.6a shows pH-value of the waste sample with time during biogas production at 30 $^0$C. The initial pH-values of waste sample A, B and C are 6.9, 6.9 and 6.8 respectively and biogas was not produced. On the 3$^{rd}$ day, production was observed for waste A, B and C and the pH-values were 6.9, 7.0 and 6.9 respectively. On the 14$^{th}$ day, an optimum biogas was produced from waste A (18.5 ml), B (17.3 ml) and C (15.8 ml) at a pH-value of 7.4, 7.5 and 7.3 respectively. When production started declining continuously on the 20$^{th}$ day, the mean pH was 7.6, 7.6 and 7.4 for waste sample A, B and C respectively. Figure 4.6b shows the pH of waste sample A, B and C during production with retention time (day) at 31 $^0$C. Production started on the 3$^{rd}$ day and the pH were 6.9, 6.9 and 6.8 respectively. At optimum production (20.2 ml, 19.7 ml and 22.6 ml for waste A, B and C) on the 14$^{th}$ day, the pH was 7.3, 7.4 and 7.4 respectively. After on the 14$^{th}$ day, there was a gradual decline in production and the mean pH were 7.6, 7.7 and 7.9 for waste A, B and C respectively with time. Figure 4.6c shows the pH of waste during production at 32 $^0$C. At pH of 6.9, 6.9 and 6.8 for waste A, B and C respectively, there was initial production observed on the 3$^{rd}$ day. On the 14$^{th}$ day optimum production of 20.7 ml, and 19.9 ml were observed for waste A and B with pH of 7.5 and 7.4 respectively. On the 15$^{th}$ day, waste C indicated an optimum production of 19.9 ml with pH 7.5. Thereafter, there was an unsteady decline in production with mean pH of 7.7, 7.4 and 7.7 for waste sample A, B and C respectively. They agreed with Khalid, et al., (2011) and Ojolo, et al., (2007), that the favorable pH for optimum biogas production was 6.5 through neutral to 7.5 while the temperature varied from 28 $^0$C to 33 $^0$C. The decline in biogas production at favorable pH is probably due to inhibitors in the digester.

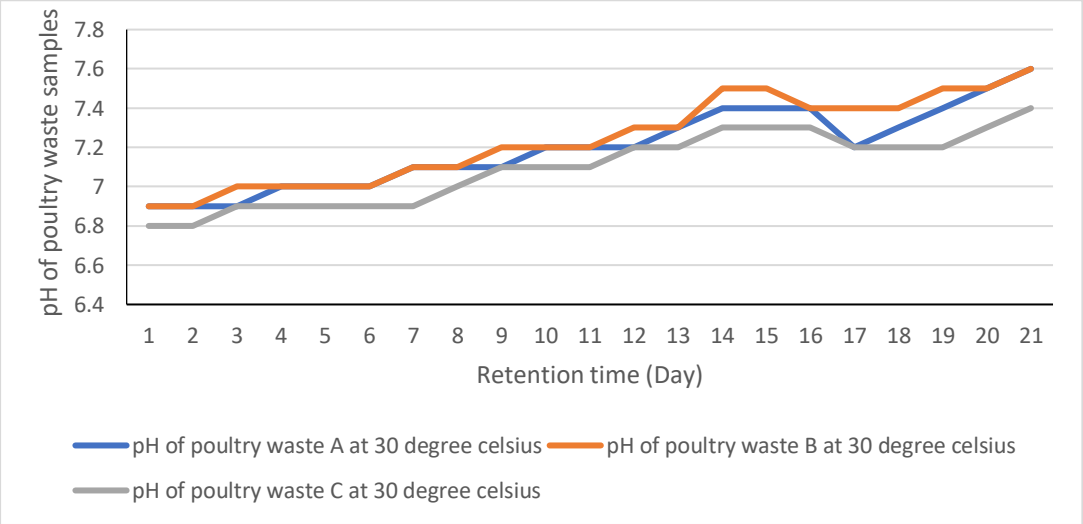



**Figure 4.6a:** pH-value of poultry waste sample A, B, and C at 30 $^0$C with retention time

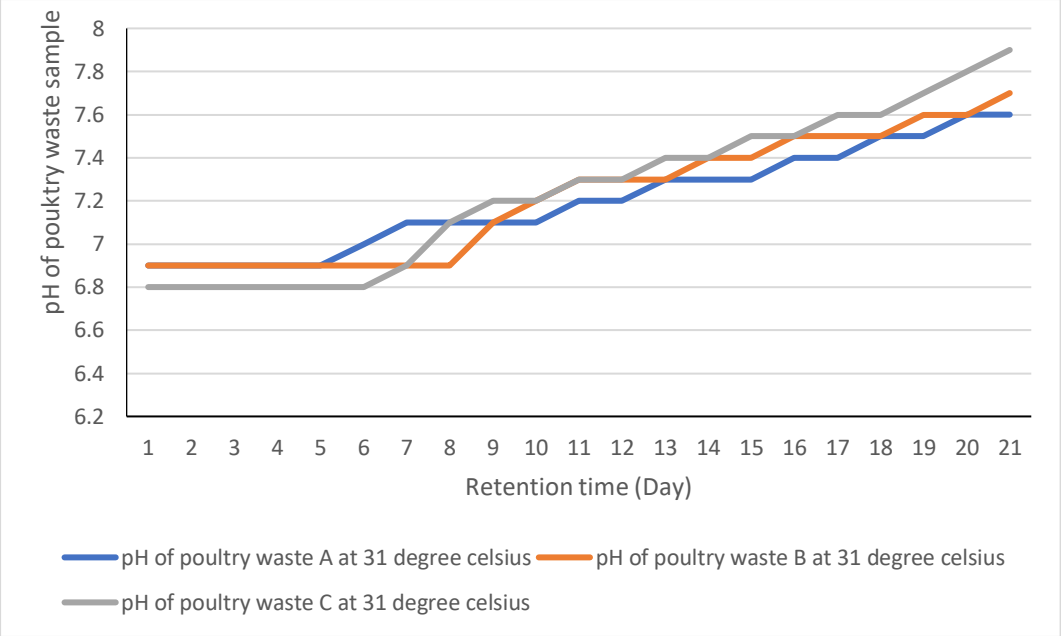



**Figure 4.6b:** pH-value of poultry waste sample A, B and C at temperature of 31 $^{0}$C with time

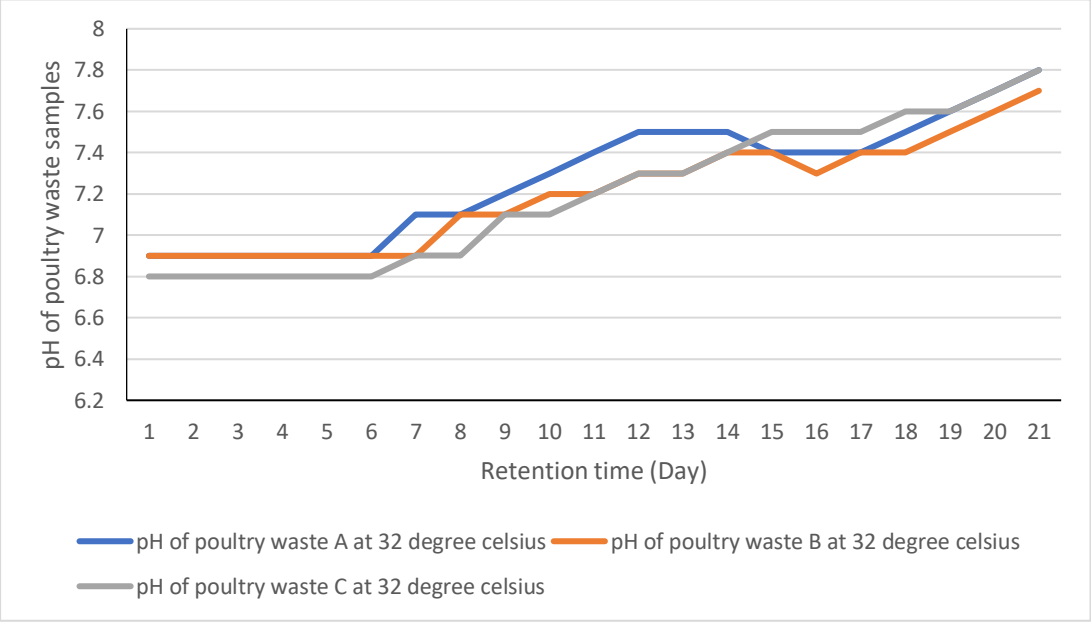



**Figure 4.6c:** pH-value of poultry waste sample A, B and C at temperature of 32 $^{0}$C with time

Figure 4.7 (a - c) compares the pH-value of each sample at 30 $^{0}$C, 31 $^{0}$C and 32 $^{0}$C with time. Figure 4.7a and 4.7b shows maximum biogas production on the 14$^{th}$ day at a pH-value of 7.5 and 7.4 respectively at 32 $^{0}$C. Figure 4.7c shows a maximum production on the 14$^{th}$ day with pH-value of 7.4 at 31 $^{0}$C. At high temperature, the most favorable pH for the waste samples is probably attributed to favor maximum biogas production. It agreed with Al Seadi, et al., (2008) study, that pH of 6.5 – 8.2 favored biogas production. Figure 4.7c is probably sensitive to inhibitors at high temperature therefore, producing high biogas at mild temperature (31 $^{0}$C) but at favorable pH-value.

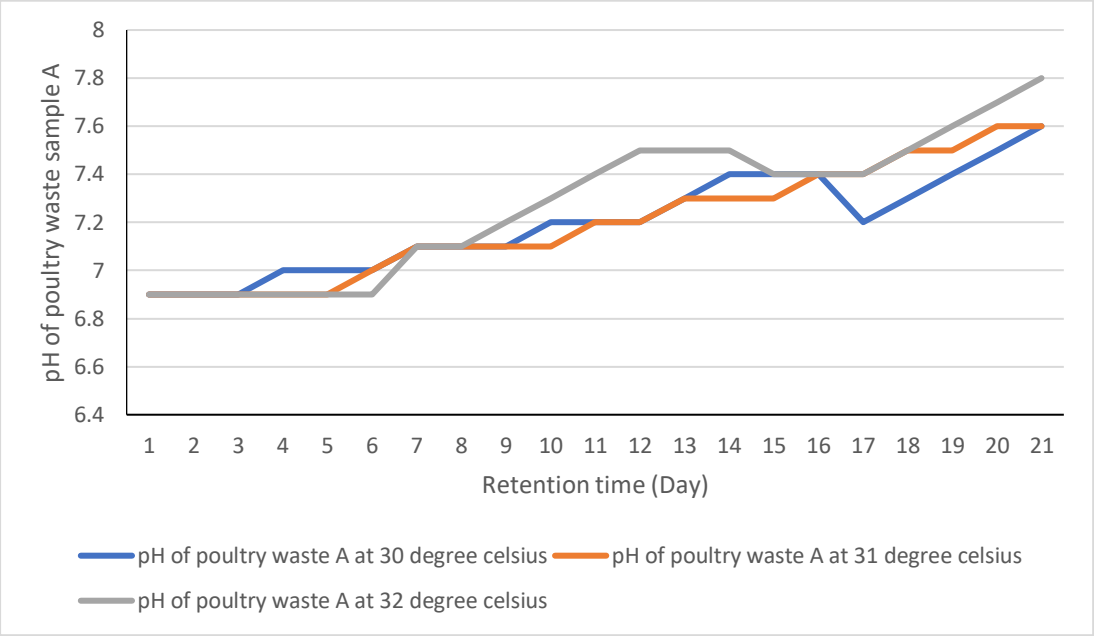



**Figure 4.7a:** Comparing pH-value of poultry waste sample A at 30 $^0$C, 31 $^0$C and 32 $^0$C with time

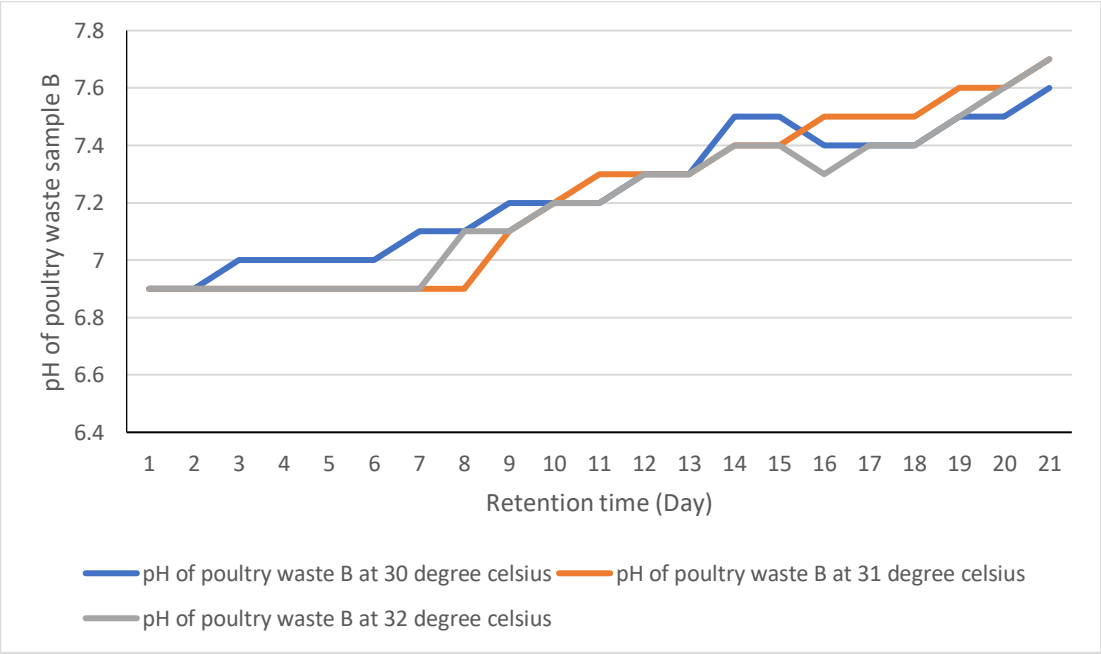



**Figure 4.7b:** Comparing pH-value of poultry waste B at 30 $^0$C, 31 $^0$C and 32 $^0$C with time

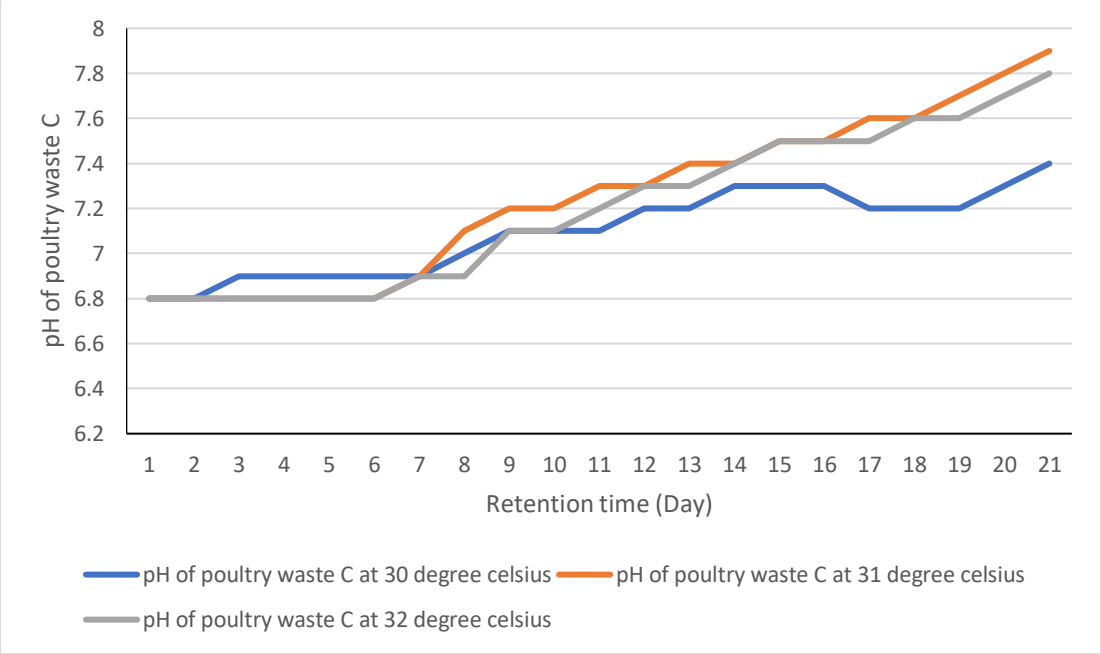



**Figure 4.7c:** Comparing pH-value of poultry waste C at 30 $^0$C, 31 $^0$C and 32 $^0$C with time

### 4.6 Results from statistical analysis using one-way ANOVA

4.6.1 Effect of temperature on pH variation

The results of the ANOVA (appendix C; table C.3) shows that temperature have a significant ($P \leq 0.05$) effect on the pH variation. As temperature increases, the pH of the waste increases. Therefore, allowing a favorable ecosystem for the AD microorganisms because they are sensitive to pH change of the slurry. It might be due to high biogas production as observed in the research study, and as reported by Ogiehor and Ovueni, (2014). The Duncan's multiple range (appendix C; table C.4, C.5, and C.6) test on the effect of temperature on pH shows that the pH variations for poultry waste samples are not different significantly ($P > 0.05$). The homogeneity of variance (appendix C; table C.2) shows that the variances (pH) are equal across poultry waste sample, thus reflecting on the conclusion that the results are not biased.

4.6.2 Effect of temperature on biogas production

The results of ANOVA (appendix C; table C.9) shows that temperature have no significant ($P > 0.05$) effect on the biogas production. The daily and total biogas production for 21 days for each temperature range (30 $^0$C, 31 $^0$C, and 32 $^0$C) indicates moderate volume of biogas differences. It might be attributed to the close range between the temperature (30 $^0$C, 31 $^0$C, and 32 $^0$C). At high temperature range, there might be a significant difference in biogas production as reported by Abouelenien, et al., (2013), and Ogiehor and Ovueni, (2014). The Duncan's multiple range (appendix C; table C.10, C.11, and C.12) test on the effect of temperature on biogas production indicates that the available temperature produces slightly the same ($P > 0.05$) quantity of biogas.

4.6.3 Effect of time on biogas production

The results of ANOVA (appendix C; table C.14) shows that the retention time have a significant ($P \leq 0.05$) effect on biogas production. As time (day) progresses, the slurry was degraded to produce high biogas. In the study, at temperature of 30 $^0$C, 31 $^0$C, and 32 $^0$C, there is significant biogas production within 15 – 30 days. It agreed with Rohjy, (2013) report that time range was required for significant biogas production at different thermal stage (Psychrophilic, Mesophilic, and Thermophilic).

**4.7 Enhancing the Energy Density of Biogas**

The heating value of the raw biogas (before removal of impurities) was 30.93 MJ/m$^3$ based on International Organization for Standardization (ISO 6976, 1995) as showed in appendix D. It agreed with Muzenda, (2014) range of heating value, which was thereafter purified and upgraded to enhance the density of biogas.

4.7.1 Raw Biogas analyzed using Gas Chromatography

Biogas from sample A at 32 $^0$C was collected using 100 µL injector. It was taken to the Gas chromatography for characterization. Significant readings of the percentage composition of $N_2$, $CH_4$, and $CO_2$ were observed at an average of 0.65, 1.00, and 1.20 minutes accordingly. Table 4.2 shows the composition of biogas before impurities treatment using GC. Methane gas was composed of 57.7 % and was the highest concentration of gas produced from the GC characterization.

**Table 4.2: Composition of biogas from Sample A, at 32 $^0$C before treatment of impurities using Gas chromatography**

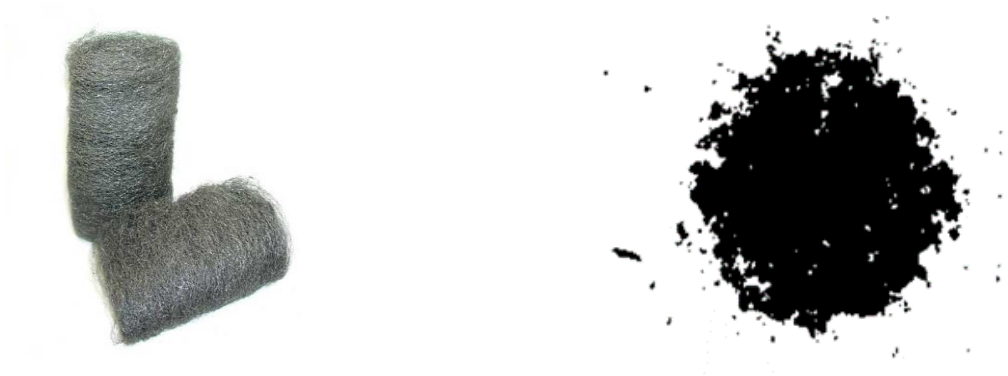
| Element | Component (%) |
|---|---|
| **$N_2$** | 0.825922083 |
| **$CH_4$** | 57.71280358 |
| **$CO_2$** | 26.81390448 |
| **Over lapped gases** | 12.64736986 |

Before the characterization of the raw biogas using GC. The GC was calibrated with concentrations of methane, carbon dioxide, and nitrogen. The GC was fitted with TCD (Thermal Conductivity Detector) known as universal detector. The GC analytical gas sequence was: nitrogen at (0.50 – 0.75) minutes; methane at (0.80 – 1.15) minutes, and carbon dioxide at (1.15 – 1.8) minutes. The sequence shows the order of GC analysis of biogas when TCD (Thermal Conductivity Detector) is used. It agreed with Rodrigues, et al., (2014) report, that TCD was used for gas measurement except for measuring component of hydrogen sulphide, and moist gases in biogas as illustrated in Table 3.3. The results from table 4.3, agreed with the studies by Jason, et al., (2014) and Al Seadi, et al., (2009). In their

analyses, methane gas, carbon dioxide, and nitrogen were estimated to be 50 – 75 %, 25 – 50 %, and 0 – 10 % respectively. The methane gas concentration was low, which probably influences the heating value (calorific value) of the analysed biogas, therefore, to improve the heating value, impurities must be removed from the biogas. From table 4.3, significant gases ($CH_4$, and $CO_2$) for the research were measured except for hydrogen sulphide and moist, other gases were observed overlapping, which represents other traces of gases composed in the biogas.

### 4.7.2 Treatment of impurities

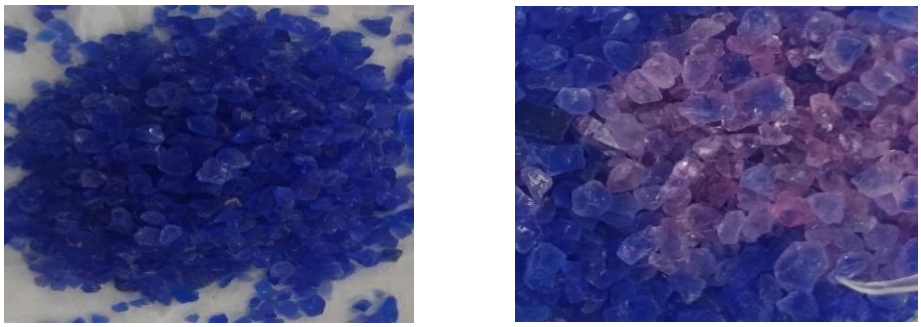
The removal of impurities from digester C (sample A at 32 $^0$C) was attained using non-costly method. Figure 4.8 shows the steel wool before, and after scrubbing, Figure 4.9 shows the silica gel before, and after absorbing the moisture content. Table 4.3 shows the weight (g) of the impurity after treating biogas with steel wool (iron oxide) for treatment of hydrogen oxide, and silica gel for treatment of moist. It was observed that fraction of the iron oxide pellets turned dark in color, dusty, and moist. It indicates that hydrogen sulfide in biogas had reacted with the iron oxide in the tube as the biogas contacted it through Dry Oxidation process. The weight of iron oxide was increased by 0.67 g, indicating that hydrogen sulfide was trapped by the iron oxide as showed in table 4.3. The tube with the iron oxide became warm to touch, shows that, heat was produced from the process of reaction. It agreed to Kapdi, et al, (2003) report. Equation 4.1 shows the chemical reactions involved between the reaction of iron oxide with hydrogen sulfide. The observed biogas that was free from $H_2S$ was allowed to flow with alkaline water in a countercurrent manner, therefore, $CO_2$ in the biogas was treated. This was possible because $CO_2$ is strongly soluble in alkaline water than $CH_4$ at ambient temperature. The alkaline water reacted strongly with $CO_2$ to produce a weak acid called carbonic acid ($H_2CO_3$) as shown in equation 4.2 and flowed out from the purification and upgrade setup. The biogas that was free of $CO_2$ flew through the top outlet connected to the cylinder containing silica gel. Figure 4.9 shows that moist in the biogas was absorbed, portion of the silica gel gradually turned from blue to pink after about 5 – 10 minutes of biogas contact with silica gel, which agreed to Chege, (2015) report. Table 4.3 shows that 5.20 g volume of moist was treated from biogas after contact with silica gel. The observed report agreed to Nallamothu, et al., (2013) report.



a. Steel wool before scrubbing b. Steel wool after scrubbing

**Figure 4.8:** Hydrogen Sulphide treatment

The colour of the silica gel was altered from blue to pink colour after it absorbed moisture from the purified biogas.



a. Dry silica gel before used b. Silica gel after moisture treatment

**Figure 4.9:** Moisture Absorber

**Table 4.3: Weight of Iron oxide, Silica gel before, and after impurity treatment from 265.6 ml of biogas produced from digester C, Sample A at 32 $^{0}$C**

| Chemical | Before Impurity removal (g) | After contact with biogas (g) | Impurity removed (g) |
|---|---|---|---|
| Iron oxide | 0.73 | 1.40 | 0.67 |
| Silica gel | 105.00 | 110.20 | 5.20 |

**Table 4.4: Gas chromatography analysis of treated biogas after impurities treatment**

| Element | Component (%) |
|---|---|
| $N_2$ | 1.27267579 |
| $CH_4$ | 84.56079534 |
| $CO_2$ | 1.34747793 |
| **Over lapped gases** | 1.26496884 |

$$Fe_2O_3 + H_2S \rightarrow Fe_2S_3 + 3H_2O \qquad Equation\ 4.1$$

$$H_20 + CO_2 \rightarrow H_2CO_3 \qquad Equation\ 4.2$$

Table 4.4 above, shows the GC analysis of the components in the biogas after impurity treatment. The percentage of Methane gas was 84.5 %, $CO_2$ was 1.3 %, nitrogen was 1.3 %, and other gases was 1.3 %. It indicates that the energy potential in Table 4.4 is higher than the energy potential from raw biogas (Table 4.2), which agreed with Chege, (2015) report, that the quality of the biogas had been enhanced. The biogas was upgraded, and was comparable to Bansal, (2013); Chege, (2015) findings. It might be because the method was efficient in the enhancement of the energy potential in biogas. Table 4.5 shows the comparison of properties of natural gas to the purified biogas from the GC analysis. It indicates that it can be allowed to flow in natural gas grid since its quality is comparable to South Africa natural gas quality. The calorific value (heating value) of the cleaned biogas was 47.63 $MJ/m^3$ after computation using International Organization for Standardization (ISO 6976, 1995). Appendix D shows the computation of the heating value of the cleaned biogas.

**Table 4.5: Comparison of Physical properties of Natural gas and Purified biogas from Results and Discussion**

| Significant Components | Unit | Natural gas[1] % | Natural gas[2] % | Dutch Natural gas[3] % | North Sea Natural gas[3] % | South Africa Natural gas[4] % | Purified Biogas % |
|---|---|---|---|---|---|---|---|
| $CH_4$ | Vol. % | 91.0 | 97 | 81 | 87 | 81-87 | 84.6 |
| $CO_2$ | Vol. % | 0.61 | 2 | 1.2 | 1 | 0.1–1.0[5] | 1.3 |
| $N_2$ | Vol. % | 0.32 | 1 | 0.3 | 14 | 1.3–5.6[5] | 1.3 |

[1] (Chege, 2015); [2](Saikkonen, 2006); [3](Persson, et al., 2006); [4] (Department of Minerals and Energy, 2005); [5](Demirbas, 2010).

## 4.8 Techno-economic analysis

The digester required about 4,000 kg per year of poultry waste which would roughly fill 10 $m^3$ space after mixing with water. The rest 10 $m^3$ volume of the digester would be available for the produced biogas in the digester. 4,000 kg of waste can produce about 240 $m^3$ of biogas which can generate about 2,160 kWh of energy per year as reported by Singh, et al., (2008): that 50 kg of poultry waste generated about 3 $m^3$ of biogas and about 27 kWh. An annual average electricity consumption per household in the rural area was estimated to be about 2,501 kWh as reported by Magambo, (2010). To ensure the sustainability and viability of the system, techno economic analysis was carried out. The following sections discussed the economic analysis considering the costs involved in the construction of biogas digester. The economic analysis results were presented in terms of investment and payback time.

### 4.8.1 Input data

The data used in the techno-economic analysis are explained below. The values presented are all estimated cost of materials in South Africa.

#### 4.8.1.1 Investment cost

The investment cost represents the total amount of money invested for the project. The fixed dome small-scale digester (20 $m^3$) was considered for economic analysis in this study. The cost of different materials and components for construction of the digester is giving in table 4.6. The cost of land was not included in the analysis, it was assumed that the land was made available by the owner of the system and cost of generator for distribution was not considered. The cash flow is the earnings before depreciation of the digester. In the study, energy production was used by the family as electrical energy, and not sold to the public. Therefore, sales of energy for income was not considered. Compost sale, incentives from Eskom, and from the South African government was considered as cash inflow (Creamer, 2013). The cash outflow refers to payments for goods purchased for building the fixed dome digester and maintenance cost was considered.

**Table 4.6: Estimated Investment cost of constructing 20 $m^3$ fixed dome digester**

| Item | Description | Unit | Amount (Rand) |
|---|---|---|---|
| 1 | Site clearance and removing of top most part of the vegetation where the fixed dome needed to be constructed | 16 $m^2$ | 2000 |
| 2 | Excavation of the trial hole of 3.5 m x 2.5 m x 2.5 m deep below the ground level for the fixed dome digester and back filling | 21.9 $m^3$ | 7000 |
| 3 | Casting of the fixed dome digester footing of 200 mm thick x 3.44 m x 2.44 m. Reinforced concrete of 25 mpa strength | 1.8 $m^3$ | 2440 |
| 4 | 100 mm mesh wire for the foundation footing slab 2.4 m x 3.4 m for the concreting | 3 m long | 3000 |
| 5 | Construction of retaining wall for the digester of 220 mm thick with common bricks plastering on both sides 3.4 m x 2.4 m x 2.5 m high wall up to slab level. | 3200 of common bricks | 9600 |
| 6 | 120 mm diameter high tensile iron rods at 200 mm centers. Both way reinforcement to construct the top slab that the digester needed to be sited for biogas. | 96 m of Iron rod | 3000 |
| 7 | Construction and fixing of gas proof manhole cover of 300 mm diameter inlets cover | 1 | 1500 |
| 8 | 100 mm galvanized brick force for the erection of the walls to slab level | 3 rolls i.e. 100 mm width and 20 mm length per roll or per brick. | 5000 |
| 9 | 50 kg bags of cement for the construction of the digester for both the concrete work, wall construction, and plastering of both interior, and exterior part of the retaining wall below the ground level i.e. sub-structural work | 50 | 4450 |
| 10 | 25 mm crush stone for the foundation footing and slab | 2.5 $m^3$ | 3500 |
| 11 | Building sand for the construction of the walls | 10 $m^3$ | 2500 |
| 12 | Plaster sand for the plastering of both interior and exterior wall of the retaining wall. | 2 $m^3$ | 5000 |
| 13 | 25 mm diameter PVC pipes | 10 m | 2500 |
| 14 | 25 mm diameter stop valves to control the flowing of the gas from the digester to the dome | 1 | 2000 |
| 15 | Labor work for the construction of the digester from an artisan | NA | 5000 |
| 16 | Plumbing work | NA | 2000 |
| 17 | Net Total | | 60,490.00 |

4.8.1.2 Operation and Maintenance (O & M) cost

The operation cost includes all costs for the treatment of poultry waste, wheel loader cost, operational, and administrative cost. The administrative, wheel loader and labor cost were not considered because it was not an income generating project. The energy cost incurred while building the digester was not considered because it was assumed that energy required for the O & M was produced within the digester. The maintenance cost for the digester after every 5 years was assumed to be R1,209.80 (2 % of the investment cost) as reported by Garcia, (2014). The maintenance of the fixed dome digester

was considered low compare to other family size digester because of the use of concrete, and brick materials for its construction. It is probably cheaper to maintain, and simpler to build as reported by Rajendran, et al., (2012). The insurance, and transport cost were not considered in the study. All cost was estimated and used as basis for the construction of the digester.

#### 4.8.1.3 Income

The income in the study refers to all sources of cash inflow in support of the O & M cost for the digester. The slurry after biogas production was sold out to famers to enrich their crops and cost R441. Incentives from Eskom and government was R2,592 and R2,052 respectively. It is probably an initiative from the government in encouraging the building of digester to support energy production in the country. Therefore, providing income assistance to assist in renewable energy projects. Table 4.8 shows the income generated from building a digester.

### 4.8.2 Economic analysis

In the economic analysis, two scenarios were presented: Scenario l and Scenario ll. All analysis was based on the scenarios.

Scenario l: Whereby installation of electricity for energy was from the national power grid.

Scenario ll: There was construction of fixed dome digester for energy purpose instead of installing from national power grid.

#### 4.8.2.1 Investment cost, O & M cost

The investment cost, and O & M cost for both scenario I, and scenario II was different. The O & M cost was different based on techno-economic analysis. Transportation was not considered for both. Based on Khan, (2014) finding, the Investment, and O & M costs of installing electricity for thermal energy from national power grid in an apartment was less compared to construction of fixed dome digester in same apartment. Table 4.7 shows estimated values for each scenario.

**Table 4.7: Investment, Operation & Maintenance (O & M) cost**

| Costs | Scenario l | Scenario ll |
|---|---|---|
| **Investment costs** | **Value (Rand)** | **Value (Rand)** |
| **Biogas plant construction** | NA | 60,490.00 |
| **Energy Installation** | 5,000 | NA |
| **Total Investment costs** | 5,000 (Fixed) | 60,490.00 (Fixed) |
| **O & M costs** | **Value (Rand)** | **Value (Rand)** |
| **Wheel loader costs** | NA | NA |
| **Maintenance** | NA | R1,209.80 |
| **Labor costs** | 700 | NA |
| **Total O & M costs** | 700 (Fixed) | R1,209.80 (Recurring every 5 years) |

4.8.2.2 Incomes (Cash Inflow)

Analysis on the income generated from scenario II was observed. Compost sales, tax incentive from the government and Eskom was considered. The income for scenario II is presented in table 4.8.

**Table 4.8: Income from Scenario ll**

| Income | Scenario ll Per year |
|---|---|
| Compost sales | R441.00 |
| Tax incentives | R2,052.00 |
| Eskom Incentives | R2,592.00 |
| **Total Income** | **R5,085.00** |

Table 4.8 shows the results of scenario II. Revenue was generated as illustrated in table 4.8. From appendix E in equation E.1, it indicates that it is economically feasible, and investment is profitable. In the analysis, expenses were recovered after 11.9 years i.e. 11 years and 9 months.

$$\text{Payback period} = \frac{\text{Investment required}}{\text{Net annual cash inflow}} \qquad Equation\ 4.3$$

$$\text{Payback period} = \frac{60{,}490}{5{,}085} = 11.9 \text{ years}$$

The observations agreed with Wargert, (2009); Rohjy, (2013) report, that techno-economic analysis of the fixed dome digester was cheap to practice in the rural community. The project was relatively cheap to construct and has a lifespan of 20 years. Maintenance and operational cost was relatively low because it has no rusting steel parts, no moving parts. The cost for the technology included all cost listed in table 4.6 above. From table 4.7, Operation and Maintenance cost was R1,209.80. It was the cost of general maintenance of the digester and was assumed to be 2% of the investment cost in agreement with Garcia, (2014) report. The payback period (time) was eleven years and nine months. Considering the economic analysis: value of time, transport, benefits in generating energy for personal usage, investment cost, operation and maintenance cost are dependent on the nation's economy called variable cost. They all affected the cost for both scenario l, and ll. The techno-economic analysis of the biogas project indicated that the project is financially feasible.

# Chapter 5 - Conclusion and Recommendation

The following interpretations were made from the experimental results:

The result of the current study shows significant energy potential from poultry waste if anaerobically digested. The volume of biogas produced was based on the following parameters: carbon to nitrogen balance, temperature, pH-value, retention time, inhibitors and volatile solids of the waste. High biogas production was collected from Sekela farm (waste A) than waste from Emarldene and Parkside farm because the physio-chemical characteristics were highly favorable. Observations showed that: at mesophilic temperature, the higher the temperature under a period (time) and favorable parameters, the higher the biogas yield/production. The biogas yield from waste A was higher than waste B, and C at mesophilic temperature of 32 $^0$C under 21 days due to physio-chemical characteristics which was favorable for high yield/production. Waste C at 31 $^0$C produced the highest biogas instead of waste A or B therefore, altering the expectation (favorable physio-chemical characteristics yields high biogas production). This might be due to the thorough mixing of the waste with water and it is possible that there were clumps of waste in the digester that was able to affect thermal distribution in the digester. We cannot be certain, if under same procedures of studies, maximum biogas could be produced from waste at higher temperature than 32 $^0$C. The production of biogas from waste is a primary way of mitigating environmental impact (e.g. odor) from waste, can be used as a source of thermal energy to heat up chicken in the poultry farm, for cooking and creating job opportunities.

It was observed that 1 kg of waste could produce an average amount of 265.6 ml ($2.7 \times 10^{-4}$ m$^3$) of biogas at a temperature of 32 $^0$C, which could generate about $2.4 \times 10^{-3}$ kWh of energy. It was the highest volume of biogas produced after 21 days. The production is below expected result because is not in agreement with the findings of Porras and Gebresenbet, (2003). It is possible that the pre-treatment of the waste at 100 $^0$C for 10 minutes instead of 120 $^0$C for 10 minutes, the chicken diet might be composed of high fiber than roughages, and inhibitors such as fine fraction of 0.83 mm size of sand, chips of wood, saw dust and small flaky materials might have limited the volume of production from the waste. Though, unexpected volume of biogas was produced, the slurry after digestion can be used as fertilizer for both commercial and non-commercial crops, providing long and short-term jobs for youths in the sales of fertilizer and less environmental impact from waste.

The treatment of the biogas impurities (such as water vapor, $CO_2$ and $H_2S$) by purification and upgrade, improved the methane concentration from 57.71 % to 84.56 %, thereby, the energy density was improved. It is within the South Africa natural gas range (81 – 87) %, therefore, it is satisfactory to be used in South Africa gas grid. It could be used as fuel (e.g. vehicle fuel), to generate electricity etc.

4,000 kg of waste per year could produce 240 m$^3$ of biogas to generate about 2,160 kWh of energy per year and a total income of R9,693.00 per year could be obtained by using a small sized fixed dome to

generate biogas. The results proved that: it was profitable using renewable energy as alternative source of energy. The result is partially in agreement with Magambo, (2010), which stated that 2,501 kWh of energy per year can be consumed in a rural community. It indicates that it is feasible and encouraging, to build a digester for energy production.

The 10 $m^3$ of empty vacuum in the constructed fixed dome digester was half the slurry occupied volume. It is possible that the payback time, investment cost of the digester (20 $m^3$ digester), operation and maintenance cost, labor cost and every third-party cost incurred was escalated because of the unutilized vacuum since cost is dependent on time for production. It was advised that the vacuum should be 5 $m^3$ and therefore, is likely that the payback period might be lower than 11 years and 9 months.

The payback period of 11 years and 9 months showed that it is a feasible project in rural area because it falls within the range reported by Garcia, (2014), which stated that payback period was within 20 years.

In summary, we concluded that biogas can be technically and anaerobically produced from poultry waste using feasible procedures. To improve the energy potential and density, biogas should be purified and upgraded.

# Recommendations

The following recommendations were made based on the study:

1. Poultry waste was used as feedstock to generate biogas using anaerobic digestion. The biogas produced have combustible gas and other gases as impurities, therefore, can be used for heating. Future work should be carried out in the laboratory to know how long a given volume of biogas can be used for heating in a day for a standard family.
2. Within temperatures of (30 – 32) $^0$C, result showed that the best temperature for biogas production from poultry waste was 32 $^0$C. Future study is recommended to identify the suitable temperature within (25 – 45) $^0$C for biogas production from poultry waste. It could be used as national standard in production of biogas at mesophilic temperature.
3. To improve the volume of biogas produced in AD process: future study of using mechanical agitation method, pretreating at 120 $^0$C for 10 minutes should be investigated since manual mixing/agitation of slurry and pretreatment at 110 $^0$C for 10 minutes did interrupt biogas production in the study.
4. Silica gel, iron oxide and pressurized water was used to treat moist, hydrogen sulfide and $CO_2$ in the raw biogas respectively. Future study must be investigated to determine if the purification and upgrade method is industrially viable.
5. It was techno-economic feasible to produce biogas from poultry waste in a rural community. This is feasible if land is available, no administrative cost considered and in a standard family. Future study on the techno-economic feasibility of biogas production must be investigated to determine if production is feasible: when land is not available, administrative cost is considered and urban community is considered.

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# Appendix A

Appendix A showing the Laboratory analysis and computation of percentage of TS, VS, MC and Ash of the poultry waste samples.

**Laboratory Analysis:**

**Table A.1: TS% and VS% calculation for poultry waste A, B, and C**

| Poultry waste samples | Weight of ceramic crucible (g) | Weight of crucible and poultry waste sample | Weight of waste sample (g) or ml |
|---|---|---|---|
| A | 38.56 | 41.56 | 3.00 |
| B | 44.38 | 47.38 | 3.00 |
| C | 38.56 | 41.56 | 3.00 |

**Table A.2: Weight of crucible and dried sample after heating samples to 105 $^0$C for 24 hours in an oven ($W_{total}$)**

| Poultry waste samples | $W_{total}$ (g) | Weight of sample after heating (g) |
|---|---|---|
| A | 39.52 | 0.96 |
| B | 45.19 | 0.81 |
| C | 39.52 | 0.96 |

**Table A.3: Weight of crucible and sample**

| Poultry waste samples | Weight of crucible | Weight of crucible and Initial weight of sample (g) | Weight of crucible, weight of initial sample and weight of wet sample (g) |
|---|---|---|---|
| A | 38.56 | 41.56 | 43.56 |
| B | 44.38 | 47.38 | 49.38 |
| C | 38.56 | 41.56 | 43.56 |

**Table A.4: Weight of crucible and sample after ignition at 550 $^0$C for 2 hours ($W_{volatile}$)**

| Poultry waste samples | $W_{volatile}$ (g) | Weight of sample after igniting (g) |
|---|---|---|
| A | 38.92 | 0.36 |
| B | 44.64 | 0.26 |
| C | 38.92 | 0.36 |

**Calculation of TS and VS content of poultry waste sample**

$$\text{TS (\%)} = \frac{Weight\ of\ sample\ before\ drying - weight\ of\ sample\ after\ drying}{Weight\ of\ sample\ before\ drying} \qquad \text{Equation A.1}$$

TS (g) and VS (g) gives the mass of each composition in 3g of poultry waste.

TS (g/mL) and VS (g/mL) gives the mass concentration per 2mL of water added to poultry waste.

**Table A.5: Total solids of each poultry waste sample**

| Poultry waste samples | Total solids (g) of poultry waste |
|---|---|
| A | 2.04 |
| B | 2.19 |
| C | 2.04 |

$$\text{VS (\%)} = \frac{Weight\ of\ sample\ after\ drying - weight\ of\ sample\ after\ ignition}{Weight\ of\ sample\ before\ drying} \qquad \text{Equation A.2}$$

**Table A.6: Volatile solids of each poultry waste sample**

| Poultry waste samples | VS (g) of poultry waste |
|---|---|
| A | 0.63 |
| B | 0.68 |
| C | 0.63 |

**Moisture content (MC)**

$$TS\% = 100 - MC\% \qquad \text{Equation A.3}$$

**Table A.7: Moisture content of each poultry waste sample in %**

| Poultry waste samples | MC (g) |
|---|---|
| A | 32.0 |
| B | 27.0 |
| C | 32.0 |

**Table A.8: Ash of each poultry waste in %**

| Poultry waste samples | Ash (%) |
|---|---|
| A | 12.0 |
| B | 8.7 |
| C | 12.0 |

# Appendix B

**Shows the table for the biogas production for sample A, B, and C at 30 $^0$C, 31 $^0$C, and 32 $^0$C**

**Poultry waste samples**: A, B and C

**D** = digester 1 - 9

**T** = temperature at $t_1$, $t_2$ and $t_3$;

Where $t_1$ = 30 $^0$C

$t_2$ = 31 $^0$C

$t_3$ = 32 $^0$C

**M** = Mean biogas collected

E.G. **$Ad_1t_1$** = Poultry waste sample A in digester one at temperature of 30$^0$C

**M(Ad1t1)** = Mean biogas collected from poultry waste A from digester one at temperature 30$^0$C

**Biogas yield** = $\frac{Daily\ biogas\ collected\ (ml)}{VS\ of\ the\ feedstock\ (g)}$

**Note:** Volume of water displaced is equal to the amount of biogas collected.

Two bath was used to determine the biogas available in each poultry waste sample.

**Table B.1: Temperature at 30 $^0$C, waste sample to water ration 1:3; Digester 1**

| | Biogas collected from poultry litter A (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Ad_1t_1$** | **$Ad_1t_1$** | **$Ad_1t_1$** | **Mean Biogas M($Ad_1t_1$)** | **Cumulative biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.9 | 11.8 | 12.8 | 11.8 | 11.8 | 18.7 | 6.9 |
| 4 | 14.8 | 14.5 | 15.8 | 15.0 | 26.8 | 23.8 | 7.0 |
| 5 | 12.5 | 11.1 | 10.8 | 11.5 | 38.3 | 18.3 | 7.0 |
| 6 | 19.5 | 15.5 | 15.7 | 12.4 | 50.7 | 19.7 | 7.0 |
| 7 | 14.8 | 13.9 | 13.9 | 14.2 | 64.9 | 22.5 | 7.1 |
| 8 | 9.5 | 19.8 | 18.6 | 16.0 | 80.9 | 25.4 | 7.1 |
| 9 | 9.8 | 15.7 | 14.9 | 13.5 | 94.4 | 21.4 | 7.1 |
| 10 | 11.7 | 10.5 | 10.4 | 10.9 | 105.3 | 17.3 | 7.2 |
| 11 | 9.9 | 13.4 | 11.5 | 11.6 | 116.9 | 18.4 | 7.2 |
| 12 | 15.9 | 11.8 | 14.9 | 14.2 | 131.1 | 22.5 | 7.2 |
| 13 | 13.8 | 10.7 | 9.9 | 11.5 | 142.6 | 18.3 | 7.3 |
| 14 | 20.8 | 19.0 | 15.7 | 18.5 | 161.1 | 29.4 | 7.4 |
| 15 | 15.8 | 14.0 | 10.0 | 13.3 | 174.4 | 21.1 | 7.4 |
| 16 | 10.7 | 10.5 | 10.7 | 10.6 | 185 | 16.8 | 7.4 |
| 17 | 8.6 | 16.4 | 9.9 | 11.6 | 196.6 | 18.4 | 7.2 |
| 18 | 17.0 | 19.0 | 17.7 | 17.9 | 214.5 | 28.4 | 7.3 |
| 19 | 14.7 | 10.0 | 13.9 | 12.9 | 227.4 | 20.5 | 7.4 |
| 20 | 10.0 | 10.4 | 8.9 | 9.8 | 237.2 | 15.6 | 7.5 |
| 21 | 8.0 | 8.9 | 10.0 | 9.0 | 246.2 | 14.3 | 7.6 |

**Table B.2: Temperature of 30 $^0$C, waste sample to water ratio; Digester 2**

| | Biogas collected from poultry litter B (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Bd_2t_1$** | **$Bd_2t_1$** | **$Bd_2t_1$** | **Mean Biogas M($Bd_2t_1$)** | **Cumulative biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.0 | 9.7 | 11.0 | 10.2 | 10.2 | 15.0 | 7.0 |
| 4 | 12.0 | 11.0 | 12.0 | 11.7 | 21.9 | 17.2 | 7.0 |
| 5 | 15.2 | 14.5 | 14.0 | 14.6 | 36.5 | 21.5 | 7.0 |
| 6 | 12.5 | 13.5 | 10.7 | 12.2 | 48.7 | 17.9 | 7.0 |
| 7 | 9.8 | 16.9 | 14.9 | 13.9 | 62.6 | 20.4 | 7.1 |
| 8 | 14.5 | 13.8 | 11.6 | 13.3 | 75.9 | 19.6 | 7.1 |
| 9 | 10.8 | 9.2 | 15.4 | 11.8 | 87.7 | 17.4 | 7.2 |
| 10 | 16.7 | 13.5 | 13.4 | 14.5 | 102.2 | 21.3 | 7.2 |
| 11 | 13.9 | 15.4 | 9.5 | 12.9 | 115.1 | 19.0 | 7.2 |
| 12 | 10.9 | 12.8 | 6.9 | 10.2 | 125.3 | 15.0 | 7.3 |
| 13 | 14.4 | 16.7 | 10.9 | 14.0 | 139.3 | 20.6 | 7.3 |
| 14 | 16.3 | 19.0 | 16.7 | 17.3 | 156.6 | 25.4 | 7.5 |
| 15 | 13.8 | 15.0 | 13.0 | 13.9 | 170.5 | 20.4 | 7.5 |
| 16 | 11.7 | 12.5 | 10.2 | 11.5 | 182 | 16.9 | 7.4 |
| 17 | 10.9 | 9.4 | 8.9 | 9.7 | 191.7 | 14.3 | 7.4 |
| 18 | 11.8 | 14.0 | 15.7 | 13.8 | 205.5 | 20.3 | 7.4 |
| 19 | 10.7 | 13.0 | 14.9 | 12.9 | 218.4 | 19.0 | 7.5 |
| 20 | 9.0 | 10.4 | 12.9 | 10.8 | 229.2 | 15.9 | 7.5 |
| 21 | 8.0 | 7.9 | 6.0 | 7.3 | 236.5 | 10.7 | 7.6 |

**Table B.3: Temperature of 30 $^0$C, waste sample to water ratio, Digester 3**

| | Biogas collected from poultry litter C (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Cd_3t_1$** | **$Cd_3t_1$** | **$Cd_3t_1$** | **Mean Biogas M($Cd_3t_1$)** | **Cumulative biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 3 | 10.8 | 10.4 | 9.7 | 10.3 | 10.3 | 14.7 | 6.9 |
| 4 | 12.4 | 15.3 | 14.1 | 13.9 | 24.2 | 19.9 | 6.9 |
| 5 | 10.3 | 16.1 | 12.8 | 13.1 | 37.3 | 18.7 | 6.9 |
| 6 | 13.8 | 13.5 | 15.7 | 14.3 | 51.6 | 20.4 | 6.9 |
| 7 | 16.8 | 14.9 | 12.9 | 14.9 | 66.5 | 21.3 | 6.9 |
| 8 | 13.8 | 10.8 | 13.6 | 12.7 | 79.2 | 18.1 | 7.0 |
| 9 | 16.8 | 14.7 | 10.9 | 14.1 | 93.3 | 20.1 | 7.1 |
| 10 | 13.0 | 13.5 | 13.4 | 13.3 | 106.6 | 19.0 | 7.1 |
| 11 | 10.9 | 15.4 | 13.5 | 13.3 | 119.9 | 19.0 | 7.1 |
| 12 | 10.2 | 13.8 | 13.9 | 12.6 | 132.5 | 18.0 | 7.2 |
| 13 | 11.8 | 09.7 | 11.9 | 11.1 | 143.6 | 15.9 | 7.2 |
| 14 | 11.8 | 13.0 | 12.7 | 12.5 | 156.1 | 17.9 | 7.3 |
| 15 | 16.5 | 16.0 | 15.0 | 15.8 | 171.9 | 22.6 | 7.3 |
| 16 | 13.7 | 16.5 | 12.7 | 14.3 | 186.2 | 20.4 | 7.3 |
| 17 | 09.7 | 10.4 | 09.9 | 10.0 | 196.2 | 14.3 | 7.2 |
| 18 | 12.0 | 6.0 | 11.7 | 9.9 | 206.1 | 14.1 | 7.2 |
| 19 | 10.7 | 9.0 | 13.9 | 11.2 | 217.3 | 16.0 | 7.2 |
| 20 | 9.0 | 10.4 | 10.9 | 10.1 | 227.4 | 14.4 | 7.3 |
| 21 | 9.0 | 7.9 | 09.0 | 8.6 | 236 | 12.3 | 7.4 |

Two baths were used and a new digester was provided for digestion of poultry waste at temperature of 31 $^0$C. It was done to avoid anaerobic microorganisms from the used digester from reacting in the process of biogas collection.

**Table B.4: Temperature at 31 $^0$C, waste sample to water ration 1:3, Digester 4**

| | Biogas collected from poultry litter A (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Ad_4t_2$** | **$Ad_4t_2$** | **$Ad_4t_2$** | **Mean Biogas M($Ad_4t_2$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.3 | 10.7 | 9.7 | 10.2 | 10.2 | 16.2 | 6.9 |
| 4 | 13.4 | 12.7 | 11.0 | 12.4 | 22.6 | 19.7 | 6.9 |
| 5 | 9.5 | 10.5 | 9.8 | 9.9 | 32.5 | 15.7 | 6.9 |
| 6 | 15.5 | 12.5 | 11.7 | 13.2 | 45.7 | 21.0 | 7.0 |
| 7 | 13.8 | 15.7 | 16.9 | 15.5 | 61.2 | 24.6 | 7.1 |
| 8 | 10.5 | 13.4 | 11.6 | 11.8 | 73 | 18.7 | 7.1 |
| 9 | 15.8 | 17.2 | 14.9 | 16.0 | 89 | 25.4 | 7.1 |
| 10 | 13.7 | 15.8 | 16.4 | 15.3 | 104.3 | 24.3 | 7.1 |
| 11 | 10.9 | 12.4 | 13.5 | 12.3 | 116.6 | 19.5 | 7.2 |
| 12 | 14.9 | 15.8 | 15.9 | 15.5 | 132.1 | 24.6 | 7.2 |
| 13 | 11.8 | 13.8 | 12.9 | 12.8 | 144.9 | 20.3 | 7.3 |
| 14 | 16.8 | 17.0 | 15.7 | 20.2 | 165.1 | 32.1 | 7.3 |
| 15 | 14.8 | 14.5 | 12.0 | 13.8 | 178.9 | 21.9 | 7.3 |
| 16 | 12.7 | 11.5 | 10.7 | 11.6 | 190.5 | 18.4 | 7.4 |
| 17 | 10.5 | 13.4 | 15.9 | 13.3 | 203.8 | 21.1 | 7.4 |
| 18 | 9.1 | 10.5 | 12.7 | 10.8 | 214.6 | 17.1 | 7.5 |
| 19 | 10.5 | 13.0 | 11.9 | 11.8 | 226.4 | 18.7 | 7.5 |
| 20 | 9.2 | 12.4 | 9.9 | 10.5 | 236.9 | 16.7 | 7.6 |
| 21 | 08.4 | 09.5 | 08.0 | 8.6 | 245.5 | 13.7 | 7.6 |

**Table B.5: Temperature of 31 $^0$C, waste sample to water ratio, Digester 5**

| | Biogas collected from poultry litter B (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Bd_5t_2$** | **$Bd_5t_2$** | **$Bd_5t_2$** | **Mean Biogas M($Bd_5t_2$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.7 | 10.3 | 10.2 | 10.4 | 10.4 | 15.3 | 6.9 |
| 4 | 15.4 | 15.1 | 14.5 | 15.0 | 25.4 | 22.1 | 6.9 |
| 5 | 10.2 | 11.0 | 10.5 | 10.6 | 36 | 15.6 | 6.9 |
| 6 | 11.8 | 13.7 | 11.8 | 12.4 | 48.4 | 18.2 | 6.9 |
| 7 | 13.8 | 16.9 | 15.2 | 15.3 | 63.7 | 22.5 | 6.9 |
| 8 | 17.5 | 15.6 | 12.8 | 15.3 | 79 | 22.5 | 6.9 |
| 9 | 14.8 | 12.4 | 09.2 | 12.1 | 91.1 | 17.8 | 7.1 |
| 10 | 12.7 | 09.4 | 13.7 | 11.9 | 103 | 17.5 | 7.2 |
| 11 | 10.9 | 15.5 | 12.2 | 12.9 | 115.9 | 19.0 | 7.3 |
| 12 | 14.9 | 13.9 | 15.0 | 14.6 | 130.5 | 21.5 | 7.3 |
| 13 | 11.8 | 09.9 | 10.7 | 10.8 | 141.3 | 15.9 | 7.3 |
| 14 | 20.3 | 19.7 | 19.0 | 19.7 | 161 | 29.0 | 7.4 |
| 15 | 17.8 | 15.0 | 16.0 | 16.3 | 177.3 | 24.0 | 7.4 |
| 16 | 13.2 | 12.2 | 14.5 | 13.3 | 190.6 | 19.6 | 7.5 |
| 17 | 10.9 | 08.9 | 12.4 | 10.7 | 201.3 | 15.7 | 7.5 |
| 18 | 15.5 | 12.7 | 15.2 | 14.5 | 215.8 | 21.3 | 7.5 |
| 19 | 13.7 | 10.9 | 11.8 | 12.1 | 227.9 | 17.8 | 7.6 |
| 20 | 9.4 | 8.9 | 9.4 | 9.2 | 237.1 | 13.5 | 7.6 |
| 21 | 08.0 | 07.6 | 08.9 | 8.2 | 245.3 | 12.1 | 7.7 |

**Table B.6: Temperature of 31 $^0$C, waste sample to water ratio, Digester 6**

| | Biogas collected from poultry litter C (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Cd_6t_2$** | **$Cd_6t_2$** | **$Cd_6t_2$** | **Mean Biogas M($Cd_6t_2$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 3 | 10.4 | 10.7 | 10.9 | 10.7 | 10.7 | 15.3 | 6.8 |
| 4 | 11.0 | 12.4 | 11.0 | 11.5 | 22.2 | 16.4 | 6.8 |
| 5 | 14.5 | 15.8 | 15.2 | 15.2 | 37.4 | 21.7 | 6.8 |
| 6 | 11.2 | 13.4 | 12.7 | 12.4 | 49.8 | 17.7 | 6.8 |
| 7 | 16.1 | 15.8 | 14.2 | 15.4 | 65.2 | 22.0 | 6.9 |
| 8 | 13.2 | 12.9 | 11.7 | 12.6 | 77.8 | 18.0 | 7.1 |
| 9 | 10.4 | 10.2 | 08.9 | 9.8 | 87.6 | 14.0 | 7.2 |
| 10 | 13.5 | 14.2 | 12.6 | 13.4 | 101 | 19.1 | 7.2 |
| 11 | 15.4 | 17.2 | 15.5 | 16.0 | 117 | 22.9 | 7.3 |
| 12 | 12.8 | 15.2 | 11.7 | 13.2 | 130.2 | 18.9 | 7.3 |
| 13 | 16.7 | 14.9 | 15.9 | 15.8 | 146 | 22.6 | 7.4 |
| 14 | 23.0 | 22.0 | 22.7 | 22.6 | 168.6 | 32.3 | 7.4 |
| 15 | 17.2 | 18.9 | 17.0 | 17.7 | 186.3 | 25.3 | 7.5 |
| 16 | 14.5 | 15.7 | 15.5 | 15.2 | 201.5 | 21.7 | 7.5 |
| 17 | 10.8 | 13.7 | 12.9 | 12.5 | 214 | 17.9 | 7.6 |
| 18 | 12.9 | 11.2 | 10.7 | 11.6 | 225.6 | 16.6 | 7.6 |
| 19 | 09.1 | 09.8 | 10.9 | 9.9 | 235.5 | 14.1 | 7.7 |
| 20 | 08.4 | 08.6 | 09.9 | 9.0 | 244.5 | 12.9 | 7.8 |
| 21 | 07.9 | 07.5 | 08.0 | 7.8 | 252.3 | 11.1 | 7.9 |

**Table B.7: Temperature of 32 $^0$C, waste sample to water ratio, Digester 7**

| | Biogas collected from poultry litter A (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Ad_7t_3$** | **$Ad_7t_3$** | **$Ad_7t_3$** | **Mean Biogas M($Ad_7t_3$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.4 | 10.8 | 10.0 | 10.4 | 10.4 | 16.5 | 6.9 |
| 4 | 10.9 | 12.5 | 12.0 | 11.8 | 22.2 | 18.7 | 6.9 |
| 5 | 13.5 | 15.5 | 11.5 | 13.5 | 35.7 | 21.4 | 6.9 |
| 6 | 16.2 | 13.8 | 14.8 | 14.9 | 50.6 | 23.7 | 6.9 |
| 7 | 14.0 | 15.2 | 11.8 | 13.7 | 64.3 | 21.7 | 7.1 |
| 8 | 11.6 | 12.4 | 15.5 | 13.2 | 77.5 | 21.0 | 7.1 |
| 9 | 16.5 | 15.9 | 13.2 | 15.2 | 92.7 | 24.1 | 7.2 |
| 10 | 13.2 | 12.8 | 16.3 | 14.1 | 106.8 | 22.4 | 7.3 |
| 11 | 16.9 | 15.4 | 13.9 | 15.4 | 122.2 | 24.4 | 7.4 |
| 12 | 14.0 | 13.2 | 16.5 | 14.6 | 136.8 | 23.2 | 7.5 |
| 13 | 16.9 | 17.9 | 17.8 | 17.5 | 154.3 | 27.8 | 7.5 |
| 14 | 20.8 | 21.0 | 20.4 | 20.7 | 175 | 32.9 | 7.5 |
| 15 | 17.0 | 16.5 | 16.2 | 16.6 | 191.6 | 26.3 | 7.4 |
| 16 | 15.7 | 13.5 | 12.7 | 14.0 | 205.6 | 22.2 | 7.4 |
| 17 | 18.9 | 16.2 | 15.8 | 17.0 | 222.6 | 27.0 | 7.4 |
| 18 | 14.2 | 13.7 | 12.8 | 13.6 | 236.2 | 21.6 | 7.5 |
| 19 | 13.2 | 13.0 | 09.1 | 11.8 | 248 | 18.7 | 7.6 |
| 20 | 10.9 | 10.6 | 07.8 | 9.8 | 257.8 | 15.6 | 7.7 |
| 21 | 07.2 | 08.5 | 07.6 | 7.8 | 265.6 | 12.4 | 7.8 |

**Table B.8: Temperature of 32 $^0$C, waste sample to water ratio, Digester 8**

| | Biogas collected from poultry litter B (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Bd_8t_3$** | **$Bd_8t_3$** | **$Bd_8t_3$** | **Mean Biogas M($Bd_8t_3$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.9 |
| 3 | 10.0 | 10.5 | 10.6 | 10.4 | 10.4 | 15.3 | 6.9 |
| 4 | 10.9 | 10.8 | 13.0 | 11.6 | 22 | 17.1 | 6.9 |
| 5 | 12.2 | 14.0 | 15.4 | 13.9 | 35.9 | 20.4 | 6.9 |
| 6 | 15.4 | 17.7 | 16.8 | 16.6 | 52.5 | 24.4 | 6.9 |
| 7 | 13.5 | 15.4 | 14.8 | 14.6 | 67.1 | 21.5 | 6.9 |
| 8 | 11.5 | 12.9 | 10.8 | 11.7 | 78.8 | 17.2 | 7.1 |
| 9 | 15.2 | 16.4 | 14.2 | 15.3 | 94.1 | 22.5 | 7.1 |
| 10 | 12.9 | 14.9 | 11.7 | 13.2 | 107.3 | 19.4 | 7.2 |
| 11 | 14.5 | 16.6 | 09.2 | 13.4 | 120.7 | 19.7 | 7.2 |
| 12 | 17.9 | 13.9 | 13.3 | 15.0 | 135.7 | 22.1 | 7.3 |
| 13 | 16.8 | 15.9 | 10.9 | 14.5 | 150.2 | 21.3 | 7.3 |
| 14 | 19.9 | 20.7 | 19.1 | 19.9 | 170.1 | 29.3 | 7.4 |
| 15 | 16.8 | 16.0 | 16.6 | 16.5 | 186.6 | 24.3 | 7.4 |
| 16 | 13.2 | 13.2 | 14.5 | 13.6 | 200.2 | 20.0 | 7.3 |
| 17 | 15.0 | 15.1 | 11.4 | 13.8 | 214 | 20.3 | 7.4 |
| 18 | 14.0 | 13.7 | 09.2 | 12.3 | 226.3 | 18.1 | 7.4 |
| 19 | 11.2 | 10.9 | 07.8 | 10.0 | 236.3 | 14.7 | 7.5 |
| 20 | 08.9 | 07.3 | 07.4 | 7.9 | 244.2 | 11.6 | 7.6 |
| 21 | 07.0 | 07.2 | 07.9 | 7.4 | 251.6 | 10.9 | 7.7 |

**Table B.9: Temperature of 32 $^0$C, waste sample to water ratio, Digester 9**

| | Biogas collected from poultry litter C (ml) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Day** | **$Cd_9t_3$** | **$Cd_9t_3$** | **$Cd_9t_3$** | **Mean of Biogas M($Cd_9t_3$)** | **Cumulative Biogas produced** | **Biogas yield (ml-biogas/g-VS)** | **Mean pH-value** |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 2 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 6.8 |
| 3 | 10.5 | 10.8 | 11.0 | 10.8 | 10.8 | 15.2 | 6.8 |
| 4 | 10.2 | 11.2 | 10.4 | 10.6 | 21.4 | 14.9 | 6.8 |
| 5 | 13.3 | 14.8 | 11.2 | 13.1 | 34.5 | 18.5 | 6.8 |
| 6 | 15.5 | 12.4 | 13.7 | 13.9 | 48.4 | 19.6 | 6.8 |
| 7 | 13.9 | 10.8 | 10.2 | 11.6 | 60 | 16.3 | 6.9 |
| 8 | 11.5 | 08.9 | 13.7 | 11.4 | 71.4 | 16.1 | 6.9 |
| 9 | 15.4 | 13.2 | 13.9 | 14.2 | 85.6 | 20.0 | 7.1 |
| 10 | 13.5 | 16.1 | 16.6 | 15.4 | 101 | 21.7 | 7.1 |
| 11 | 16.4 | 13.4 | 12.5 | 14.1 | 115.1 | 19.9 | 7.2 |
| 12 | 13.5 | 15.2 | 17.7 | 15.5 | 130.6 | 21.8 | 7.3 |
| 13 | 15.2 | 13.5 | 14.9 | 14.5 | 145.1 | 20.4 | 7.3 |
| 14 | 17.0 | 15.9 | 16.7 | 16.5 | 161.6 | 23.2 | 7.4 |
| 15 | 20.2 | 20.5 | 19.0 | 19.9 | 181.5 | 28.0 | 7.5 |
| 16 | 17.5 | 16.7 | 14.5 | 16.2 | 197.7 | 22.8 | 7.5 |
| 17 | 13.2 | 13.7 | 12.9 | 13.3 | 211 | 18.7 | 7.5 |
| 18 | 11.1 | 11.2 | 09.7 | 10.7 | 221.7 | 15.1 | 7.6 |
| 19 | 10.8 | 09.8 | 07.9 | 9.5 | 231.2 | 13.4 | 7.6 |
| 20 | 10.7 | 10.6 | 07.3 | 9.5 | 240.7 | 13.4 | 7.7 |
| 21 | 07.2 | 07.5 | 07.0 | 7.2 | 247.9 | 10.1 | 7.8 |

# Appendix C

## Effect of temperature on pH variation

**Oneway**

**Where:**

Var00001 = Temperature of poultry waste samples at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00002 = pH of poultry waste A at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00003 = pH of poultry waste B at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00004 = pH of poultry waste C at 30 $^0$C, 31 $^0$C, and 32 $^0$C

**Table C.1** **Descriptives**

| | | N | Mean | Std. Deviation | Std. Error | 95% Confidence Interval for Mean | | Minimum | Maximum |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Lower Bound | Upper Bound | | |
| **VAR00002** | 30.00 | 5 | 6.9400 | .05477 | .02449 | 6.8720 | 7.0080 | 6.90 | 7.00 |
| | 31.00 | 5 | 6.9000 | .00000 | .00000 | 6.9000 | 6.9000 | 6.90 | 6.90 |
| | 32.00 | 5 | 6.9000 | .00000 | .00000 | 6.9000 | 6.9000 | 6.90 | 6.90 |
| | Total | 15 | 6.9133 | .03519 | .00909 | 6.8938 | 6.9328 | 6.90 | 7.00 |
| **VAR00003** | 30.00 | 5 | 6.9600 | .05477 | .02449 | 6.8920 | 7.0280 | 6.90 | 7.00 |
| | 31.00 | 5 | 6.9000 | .00000 | .00000 | 6.9000 | 6.9000 | 6.90 | 6.90 |
| | 32.00 | 5 | 6.9000 | .00000 | .00000 | 6.9000 | 6.9000 | 6.90 | 6.90 |
| | Total | 15 | 6.9200 | .04140 | .01069 | 6.8971 | 6.9429 | 6.90 | 7.00 |
| **VAR00004** | 30.00 | 5 | 6.8600 | .05477 | .02449 | 6.7920 | 6.9280 | 6.80 | 6.90 |
| | 31.00 | 5 | 6.8000 | .00000 | .00000 | 6.8000 | 6.8000 | 6.80 | 6.80 |
| | 32.00 | 5 | 6.8000 | .00000 | .00000 | 6.8000 | 6.8000 | 6.80 | 6.80 |
| | Total | 15 | 6.8200 | .04140 | .01069 | 6.7971 | 6.8429 | 6.80 | 6.90 |

**Table C.2**

**Test of Homogeneity of Variances**

| | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|
| **VAR00002** | 96.000 | 2 | 12 | .000 |
| **VAR00003** | 96.000 | 2 | 12 | .000 |
| **VAR00004** | 96.000 | 2 | 12 | .000 |

**Table C.3**

**ANOVA**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| **VAR00002** | Between Groups | .005 | 2 | .003 | 2.667 | .110 |
| | Within Groups | .012 | 12 | .001 | | |
| | Total | .017 | 14 | | | |
| **VAR00003** | Between Groups | .012 | 2 | .006 | 6.000 | .016 |
| | Within Groups | .012 | 12 | .001 | | |
| | Total | .024 | 14 | | | |
| **VAR00004** | Between Groups | .012 | 2 | .006 | 6.000 | .016 |
| | Within Groups | .012 | 12 | .001 | | |
| | Total | .024 | 14 | | | |

**Table C.4 VAR00002**

**Duncan[a]**

| | | Subset for alpha = 0.05 |
|---|---|---|
| **VAR00001** | **N** | **1** |
| 31.00 | 5 | 6.9000 |
| 32.00 | 5 | 6.9000 |
| 30.00 | 5 | 6.9400 |
| Sig. | | .081 |

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

**Table C.5 VAR00003**

**Duncan[a]**

| | | Subset for alpha = 0.05 | |
|---|---|---|---|
| **VAR00001** | **N** | **1** | **2** |
| 31.00 | 5 | 6.9000 | |
| 32.00 | 5 | 6.9000 | |
| 30.00 | 5 | | 6.9600 |
| Sig. | | 1.000 | 1.000 |

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

**Table C.6 VAR00004**

**Duncan[a]**

| | | Subset for alpha = 0.05 | |
|---|---|---|---|
| **VAR00001** | **N** | **1** | **2** |
| 31.00 | 5 | 6.8000 | |
| 32.00 | 5 | 6.8000 | |
| 30.00 | 5 | | 6.8600 |
| Sig. | | 1.000 | 1.000 |

Means for groups in homogeneous subsets are di splayed.

a. Uses Harmonic Mean Sample Size = 5.000.

**Effect of temperature on biogas collection**

**Oneway**

Where:

Var00001 = Temperature of poultry waste samples at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00002 = Biogas collected from poultry waste A at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00003 = Biogas collected from poultry waste B at 30 $^0$C, 31 $^0$C, and 32 $^0$C

Var00004 = Biogas collected from poultry waste C at 30 $^0$C, 31 $^0$C, and 32 $^0$C

**Table C.7** **Descriptives**

| | | N | Mean | Std. Deviation | Std. Error | 95% Confidence Interval for Mean Lower Bound | 95% Confidence Interval for Mean Upper Bound | Minimum | Maximum |
|---|---|---|---|---|---|---|---|---|---|
| **VAR00002** | 30.00 | 5 | 7.6600 | 7.12587 | 3.18679 | -1.1879 | 16.5079 | .00 | 15.00 |
| | 31.00 | 5 | 6.5000 | 6.01166 | 2.68849 | -.9645 | 13.9645 | .00 | 12.40 |
| | 32.00 | 5 | 7.1400 | 6.60969 | 2.95594 | -1.0670 | 15.3470 | .00 | 13.50 |
| | Total | 15 | 7.1000 | 6.12839 | 1.58234 | 3.7062 | 10.4938 | .00 | 15.00 |
| **VAR00003** | 30.00 | 5 | 7.3000 | 6.84909 | 3.06301 | -1.2043 | 15.8043 | .00 | 14.60 |
| | 31.00 | 5 | 7.2000 | 6.82495 | 3.05221 | -1.2743 | 15.6743 | .00 | 15.00 |
| | 32.00 | 5 | 7.1800 | 6.67398 | 2.98469 | -1.1068 | 15.4668 | .00 | 13.90 |
| | Total | 15 | 7.2267 | 6.28018 | 1.62154 | 3.7488 | 10.7045 | .00 | 15.00 |
| **VAR00004** | 30.00 | 5 | 7.4600 | 6.93996 | 3.10364 | -1.1571 | 16.0771 | .00 | 13.90 |
| | 31.00 | 5 | 7.4800 | 7.03612 | 3.14665 | -1.2565 | 16.2165 | .00 | 15.20 |
| | 32.00 | 5 | 6.9000 | 6.37495 | 2.85096 | -1.0155 | 14.8155 | .00 | 13.10 |
| | Total | 15 | 7.2800 | 6.29242 | 1.62470 | 3.7954 | 10.7646 | .00 | 15.20 |

**Table C.8**

**Test of Homogeneity of Variances**

| | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|
| **VAR00002** | .357 | 2 | 12 | .707 |
| **VAR00003** | .003 | 2 | 12 | .997 |
| **VAR00004** | .095 | 2 | 12 | .910 |

**Table C.9**

**ANOVA**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| **VAR00002** | Between Groups | 3.376 | 2 | 1.688 | .039 | .962 |
| | Within Groups | 522.424 | 12 | 43.535 | | |
| | Total | 525.800 | 14 | | | |
| **VAR00003** | Between Groups | .041 | 2 | .021 | .000 | 1.000 |
| | Within Groups | 552.128 | 12 | 46.011 | | |
| | Total | 552.169 | 14 | | | |
| **VAR00004** | Between Groups | 1.084 | 2 | .542 | .012 | .988 |
| | Within Groups | 553.240 | 12 | 46.103 | | |
| | Total | 554.324 | 14 | | | |

**Table C.10 VAR00002**

**Duncan[a]**

| VAR00001 | N | Subset for alpha = 0.05<br>1 |
|---|---|---|
| 31.00 | 5 | 6.5000 |
| 32.00 | 5 | 7.1400 |
| 30.00 | 5 | 7.6600 |
| Sig. | | .796 |

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

**Table C.11 VAR00003**

**Duncan[a]**

| VAR00001 | N | Subset for alpha = 0.05<br>1 |
|---|---|---|
| 32.00 | 5 | 7.1800 |
| 31.00 | 5 | 7.2000 |
| 30.00 | 5 | 7.3000 |
| Sig. | | .979 |

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

**Table C.12 VAR00004**

**Duncan[a]**

| VAR00001 | N | Subset for alpha = 0.05<br>1 |
|---|---|---|
| 32.00 | 5 | 6.9000 |
| 30.00 | 5 | 7.4600 |
| 31.00 | 5 | 7.4800 |
| Sig. | | .900 |

Means for groups in homogeneous subs
ets are displayed.
a. Uses Harmonic Mean Sample Size =
5.000.

**Effect of time on biogas production**

**Oneway**

Where:

Var00002 = Biogas collected from poultry waste A at $30^0$C, $31^0$C, and $32^0$C

Var00003 = Biogas collected from poultry waste B at $30^0$C, $31^0$C, and $32^0$C

Var00004 = Biogas collected from poultry waste C at $30^0$C, $31^0$C, and $32^0$C

**Table C.13** **Descriptives**

| | | | | | | 95% Confidence Interval for Mean | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | Std. Deviation | Std. Error | Lower Bound | Upper Bound | Minimum | Maximum |
| **VAR00002** | 1.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 2.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 3.00 | 3 | 10.8000 | .87178 | .50332 | 8.6344 | 12.9656 | 10.20 | 11.80 |
| | 4.00 | 3 | 13.0667 | 1.70098 | .98206 | 8.8412 | 17.2921 | 11.80 | 15.00 |
| | 5.00 | 3 | 11.6333 | 1.80370 | 1.04137 | 7.1527 | 16.1140 | 9.90 | 13.50 |
| | Total | 15 | 7.1000 | 6.12839 | 1.58234 | 3.7062 | 10.4938 | .00 | 15.00 |
| **VAR00003** | 1.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 2.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 3.00 | 3 | 10.3333 | .11547 | .06667 | 10.0465 | 10.6202 | 10.20 | 10.40 |
| | 4.00 | 3 | 12.7667 | 1.93477 | 1.11704 | 7.9604 | 17.5729 | 11.60 | 15.00 |
| | 5.00 | 3 | 13.0333 | 2.13620 | 1.23333 | 7.7267 | 18.3399 | 10.60 | 14.60 |
| | Total | 15 | 7.2267 | 6.28018 | 1.62154 | 3.7488 | 10.7045 | .00 | 15.00 |
| **VAR00004** | 1.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 2.00 | 3 | .0000 | .00000 | .00000 | .0000 | .0000 | .00 | .00 |
| | 3.00 | 3 | 10.6000 | .26458 | .15275 | 9.9428 | 11.2572 | 10.30 | 10.80 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 4.00 | 3 | 12.0000 | 1.70587 | .98489 | 7.7624 | 16.2376 | 10.60 | 13.90 |
| | 5.00 | 3 | 13.8000 | 1.21244 | .70000 | 10.7881 | 16.8119 | 13.10 | 15.20 |
| | Total | 15 | 7.2800 | 6.29242 | 1.62470 | 3.7954 | 10.7646 | .00 | 15.20 |

**Table C.14**

**ANOVA**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| **VAR00002** | Between Groups | 511.987 | 4 | 127.997 | 92.662 | .000 |
| | Within Groups | 13.813 | 10 | 1.381 | | |
| | Total | 525.800 | 14 | | | |
| **VAR00003** | Between Groups | 535.529 | 4 | 133.882 | 80.458 | .000 |
| | Within Groups | 16.640 | 10 | 1.664 | | |
| | Total | 552.169 | 14 | | | |
| **VAR00004** | Between Groups | 545.424 | 4 | 136.356 | 153.209 | .000 |
| | Within Groups | 8.900 | 10 | .890 | | |
| | Total | 554.324 | 14 | | | |

# Appendix D

## Shows the computation of the heating value of biogas before and after removal of impurities

The calorific value calculator was used to determine the calorific value of the raw biogas and the biogas after removal of required impurities. Table D.1 and Table D.2 shows the picture diagram of calorific value calculator of raw biogas and biogas after removal of required impurities respectively (ISO 6976, 1995).

Raw biogas calorific value = 7.84 kWh/kg

Biogas after purification = 12.74 kWh/kg

Energy potential = Heating value x Biogas collected (MJ/ml)

**Natural Gas Calorific Value Calculator**

Table D.1: Showing the calorific value of raw biogas

Input:

| | |
|---|---|
| Methane (%) | 57.7 |
| Ethane (%) | 0.2 |
| Propane (%) | 0.1 |
| n-Butane (%) | 0.3 |
| 2-Methylpropane (%) | 0.2 |
| n-Hexane (%) | 0.2 |
| n-Heptane (%) | 0.2 |
| n-Octane (%) | 0.2 |
| n-Nonane (%) | 0.2 |
| n-Decane (%) | 0.1 |
| Ethylene (%) | 0.0 |
| Propylene (%) | 0.0 |
| 1-Butene (%) | 0.1 |
| Cis-2-Butene (%) | 0.4 |
| Trans-2-Butene (%) | 2.0 |
| 2-Methylpropene (%) | 5.0 |
| 1-pentene (%) | 4.4 |
| Nitrogen (%) | 0.8 |
| Oxygen (%) | 0.6 |
| Carbon dioxide (%) | 26.8 |
| **Total (%)** | **100** |

Results:

| | |
|---|---|
| Combustion reference temperature ($^0$C) | 15.0 |
| Metering reference temperature (0C) | 15.0 |
| Metering reference pressure (kPa) | 101.33 |
| Mean molecular weight (g/mol) | 30.45 |
| Superior (gross) calorific value (KJ/mol) | 938.88 |
| Inferior (net) calorific value (kJ/mol) | 858.98 |
| Superior (gross) calorific value (MJ/kg) | 30.84 |
| Superior (gross) calorific value (MJ/m$^3$) | 39.93 |
| Inferior (net) calorific vale (kWh/kg) | 7.84 |
| Superior (gross) calorific value (kWh/kg) | 8.57 |

References

ISO 6976 (1995) Natural gas – Calculation of calorific values, density, relative density and Wobbe Index from composition

**Natural Gas Calorific Value Calculator**

Table D.2: Showing the calorific value of biogas after impurities removal

| Input: | |
|---|---|
| Methane (%) | 84.6 |
| Ethane (%) | 0.2 |
| Propane (%) | 0.2 |
| n-Butane (%) | 0.2 |
| 2-Methylpropane (%) | 0.2 |
| n-Hexane (%) | 0.1 |
| n-Heptane (%) | 0.5 |
| n-Octane (%) | 0.2 |
| n-Nonane (%) | 0.2 |
| n-Decane (%) | 0.5 |
| Ethylene (%) | 0.5 |
| Propylene (%) | 1.0 |
| 1-Butene (%) | 3.0 |
| Cis-2-Butene (%) | 2.0 |
| Trans-2-Butene (%) | 2.0 |
| 2-Methylpropene (%) | 0.5 |
| 1-pentene (%) | 0.5 |
| Nitrogen (%) | 1.3 |
| Oxygen (%) | 0.6 |
| Carbon dioxide (%) | 1.3 |
| **Total (%)** | **100** |

| Results: | |
|---|---|
| Combustion reference temperature ($^0$C) | 15.0 |
| Metering reference temperature (0C) | 15.0 |
| Metering reference pressure (kPa) | 101.33 |
| Mean molecular weight (g/mol) | 22.28 |
| Superior (gross) calorific value (KJ/mol) | 1121.53 |
| Inferior (net) calorific value (kJ/mol) | 1021.33 |
| Superior (gross) calorific value (MJ/kg) | 50.35 |
| Superior (gross) calorific value (MJ/m$^3$) | 47.63 |
| Inferior (net) calorific vale (kWh/kg) | 12.74 |
| Superior (gross) calorific value (kWh/kg) | 13.99 |

References

ISO 6976 (1995) Natural gas – Calculation of calorific values, density, relative density and Wobbe Index from composition

# Appendix E

**Shows the financial evaluation of the fixed dome digester**

$$\textbf{Payback period} = \frac{\textbf{Investment required}}{\textbf{Net annual cash inflow}} \qquad \text{Equation E.1}$$

$$\textbf{Payback period} = \frac{60{,}490}{5{,}085} = 11.9 \text{ years}$$

1 ton of poultry waste = 907.185kg of poultry waste Equation E.2

∴ 4.409 ton of poultry waste is same as 4, 000kg of poultry waste

If 1 ton of poultry waste cost R100 ∴ 4.409ton cost R441\yr

**Calculation of Incentive**

| | |
|---|---|
| kWh per annum | 2,160kWh |
| Tax incentive rate | R0.95 |
| **Tax Incentive** | **R2,052.00** |
| Marginal Tax Rate of Entity | 0% |
| **Tax Saving** | **R2,052.00** |

**Marginal tax rate**: - Is the rate at which you pay yearly income tax. According to SARS, tax income within R0 – R78,150.00, the rate of tax is 0% of taxable income. In the study, the tax incentive is R2,052.00. It is within the tax income of R0 – R78,150.00.