AN INVESTIGATION INTO THE OPTIMISATION OF SMALL SCALE ANAEROBIC DIGESTION PROCESS SYSTEMS FOR RURAL SOUTH AFRICA

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ABSTRACT

South Africa's rural communities have been historically characterised by persistent service delivery challenges, including: lack of waste management services, poor access to reliable sanitation systems, and inconsistent and unaffordable energy options. Although the viability of biogas as decentralised waste management, sanitation, and energy solutions for rural areas within the Global South has been well documented within contemporary literature, biogas interventions within South Africa have not been successful for a variety of reasons, namely, limited research and implementation, despite a readily abundant supply of suitable feedstock within rural contexts.

The purpose of this study is to contribute to the development of a best practice model for rural biogas provision in South Africa. It is contextualised within two interrelated but distinct rural bioenergy projects located in Ndwedwe Local Municipality (NLM), KwaZulu-Natal, funded by the South African National Energy Development Institute (SANEDI) and the National Lotteries Commission (NLC); these encompass 26 household digesters and integrated biogas provision and sanitation systems at five Early Childhood Development Centres (ECDCs). Utilising a mixed-methodological approach, interventions were evaluated on their socio-economic, energy, and sanitation outcomes, and an optimisation plan was implemented to address identified shortcomings. In addition, locally available feedstock, such as cow dung, food waste, and human excreta, were characterised and analysed in order to develop optimised feeding regimens, appropriate for specific contexts and available waste streams. Finally, the development and testing of an optimised prototype digester design, based on the Chinese Fixed Dome Digester (CFDD), demonstrated superior biogas output at a higher organic loading rate (OLR) when compared to a control. This optimised design would enable digestion of larger quantities of organic waste which would be expected at a higher economy of scale. In conclusion, this study finds that the issues that have hindered the successful implementation of biogas interventions in rural areas are manifold, but can be eliminated or optimised to produce better waste management, sanitation or energy outcomes. These proposed opimitisations in design and implementation should inform future biogas interventions in KwaZulu-Natal, while contributing to a best practice model for rural biogas provision in South Africa.

DECLARATION

I, JONATHAN OLAL OGWANG, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced
    b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.
5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Student Signature: 

Date: 01 January 2020

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LIST OF ABBREVIATIONS

ABP6-Agama Biogas Pro 6

ATH- Allyl-Thiourea

BMP - Biochemical Methane Potential

BOD - Biological Oxygen Demand

C/N- Carbon to Nitrogen ratio

CFDD- Chinese Fixed Dome Digester

COD - Chemical Oxygen Demand

ECDC- Early Childhood Development Centre

GHG-Greenhouse Gases

HDPE-High Density Polyethylene

HRT-Hydraulic Retention Time

H_2S - Hydrogen Sulphide

LCFA-Long Chain Fatty Acids

LLDPE-Linear Low Density Polyethylene

MC - Moisture Content

OLR-Organic Loading Rate

LPG-Liquefied Petroleum Gas

RI- Respiratory Index

SD- Standard Deviation

SRT- Solid Retention Time

TS - Total Solids

TSS- Total Suspended Solids

UASB- Up Flow Anaerobic Sludge Blanket

VFA- Volatile Fatty Acid

VS - Volatile Solids

1. INTRODUCTION

1.1. Introduction

This chapter introduces the research by presenting the problem statement which speaks to the aim of the overall study. The chapter outlines of the study motivation, research question, research overview, aims, and objectives. In addition, each chapter has been summarised briefly.

1.2. Motivation/ Problem Statement

South Africa's rural communities are often associated with poor service delivery, including inadequate organic waste management and energy provision, despite being home to more than 35% of the nation's population. These challenges are compounded by the associated health and sustainability concerns attributable to poor organic waste management and the current large scale use of wood and fossil fuels, prompting the need for the promotion of a sustainable, affordable energy source and integrated waste management strategies. One possible alternative, anaerobic digestion, has been shown, through past state-funded initiatives, to have the potential to serve as an alternative energy source for the rural poor within a South African context. Anaerobic digesters, if installed as part of an integrated system, can also aid in the treatment and safe disposal of organic waste. However, the anaerobic digestion systems that have been implemented within South Africa have only been qualified successes, with a number of persistent issues arising related to the digester technologies, associated infrastructural components, maintenance, operation, and beneficiary engagement. Moreover, limited research has been performed towards developing a best practice model for the provision of anaerobic digestion systems in rural communities, as well as investigation of locally available feedstock.

The purpose of this study was to develop a best practice model for rural, decentralised biogas provision within KwaZulu-Natal. In addition, organic waste streams have been investigated and assessed in order to analyse possible behaviour of various substrates during anaerobic digestion. This study forms part of two projects funded by South African National Energy Development Institute (SANEDI) and the National Lotteries Commission (NLC) respectively. The purpose of the first project is to identify issues associated with twenty-six anaerobic digestion process systems that were installed by SANEDI with the aim of rectifying identified issues and providing sustainable recommendations for optimised systems. The second project introduces new biogas interventions, with the design and implementation of five integrated anaerobic digestion process systems within purposely selected early childhood development centres (ECDCs) in Ndwedwe, KwaZulu-Natal.

The final aspect of this study is to contribute to the design and testing of a new experimental anaerobic digester design which incorporated optimisations identified during a comprehensive literature survey of available technologies and through empirical work conducted in the previous phases. To meet this objective a prototype was designed based on the Chinese fixed dome digester (CFDD) using no mechanical parts. Optimisations to the digester enable it to be fabricated as one unit, provide pressure to the gas, and enable it to more successfully manage high loading rates. These findings show the development of a potential digester typology that could be up-scaled and commercialised within a rural South African context.

1.3. Research Question(s)

The overall purpose of this study is to contribute to the development of a best practice model for decentralised biogas provision within rural communities in South Africa, and KwaZulu-Natal (KZN) in particular. It does this through the examination of 26 household anaerobic digestion process systems installed through the South African National Energy Development Institute as well as through the design and implementation of five purpose-built integrated biogas and sanitation interventions at Early Childhood Development Centres (ECDCs) in NLM, KZN. In addition, a novel, optimised anaerobic digester design has been designed, tested and critically evaluated. To guide this research process, two main research questions were identified:

- Considering technology, infrastructure, and process design, what is the most cost-efficient, sustainable, and reliable model for rural decentralised biogas provision within both household and institutional contexts?
- Of the feedstock locally available within NLM, which are most analytically suitable for biogas production and contextually appropriate for project sustainability?

1.4. Research Aims and Objectives

As previously described, the overall aim of this study is to contribute to the development of a best practice model for decentralised biogas provision within rural communities in South Africa, and KwaZulu-Natal in particular. To this end, the following sub-aims have been identified:

1.4.1. Aims

- To evaluate the performance and compare the technical specifications of micro-digester technologies available within South Africa.

- To assess the performance of 26 household anaerobic digestion process systems installed in the NLM area based on the technology, process and infrastructural components.
- To develop and implement optimisations for the aforementioned 26 digester systems which address identified weaknesses and contribute to the long-term sustainability of the interventions.
- To identify, characterise, and investigate locally available feedstock and propose ideal feeding regimens for specific biogas interventions.
- To design and implement an integrated biogas and sanitation system at five ECDCs in NLM in order to evaluate the energy and sanitation outcomes of such an intervention.
- To evaluate the socio-economic impacts of biogas interventions within rural South African households and institutions.
- To develop and test an optimised lab-scale anaerobic biogas digester design which can be utilised within rural South African contexts.

1.4.2. Objectives

The aims articulated above express the intent and direction of this study. In order to achieve these aims a number of objectives have been identified, including:

- To provide a flow chart that presents an optimisation of the technical aspects of a small scale anaerobic digester for rural areas in South Africa.
- To assess the infrastructural, biochemical process and technology aspects of the 26 anaerobic digestion process systems.
- To design an optimised anaerobic digestion process system for five selected sites.
- To investigate the bio-chemical characteristics and bio-methane potential (BMP) of typical organic substrates with reference to the case studies.
- To design and test an optimised anaerobic digester prototype based on the CFDD to investigate performance in terms of gas quantity generated.

1.5. Structure of Research

The research was conducted by compiling the following chapters; a brief description of each has been provided below.

1.5.1. Chapter 1

Chapter One presents the motivation for the study with an outline of the main research question as well as the aims and objectives of the study which should be achieved at the end of the study

1.5.2. Chapter 2

Chapter Two presents a review of current available literature relevant to the study. The current issues regarding the waste management, energy and the state of biogas in rural South Africa have been focused on in greater detail. Details about anaerobic digestion and digesters has been thoroughly reviewed and described to provide understanding and aid the research.

1.5.3. Chapter 3

The case study is introduced and described in detail. Methods utilised to generate the results that are outlined, analysed, and discussed are presented in this chapter. This chapter comprises of the methods used in data collection, sampling, and explains the calculations used to generate results. Limitations of the methodology are also discussed in this chapter.

1.5.4. Chapter 4

Chapter Four presents a detailed analysis and discussion of the results obtained using the methods outlined in Chapter Three. Chapter Four presents results that meet the aims and objectives of this study

1.5.5. Chapter 5

A conclusion of the research is presented in this chapter. Chapter Four provides answers to the research questions and critically reviews the aims and objectives of the study. The chapter finally provides recommendations for future biogas interventions and research. An overall research layout is shown in Figure 1-1 below:

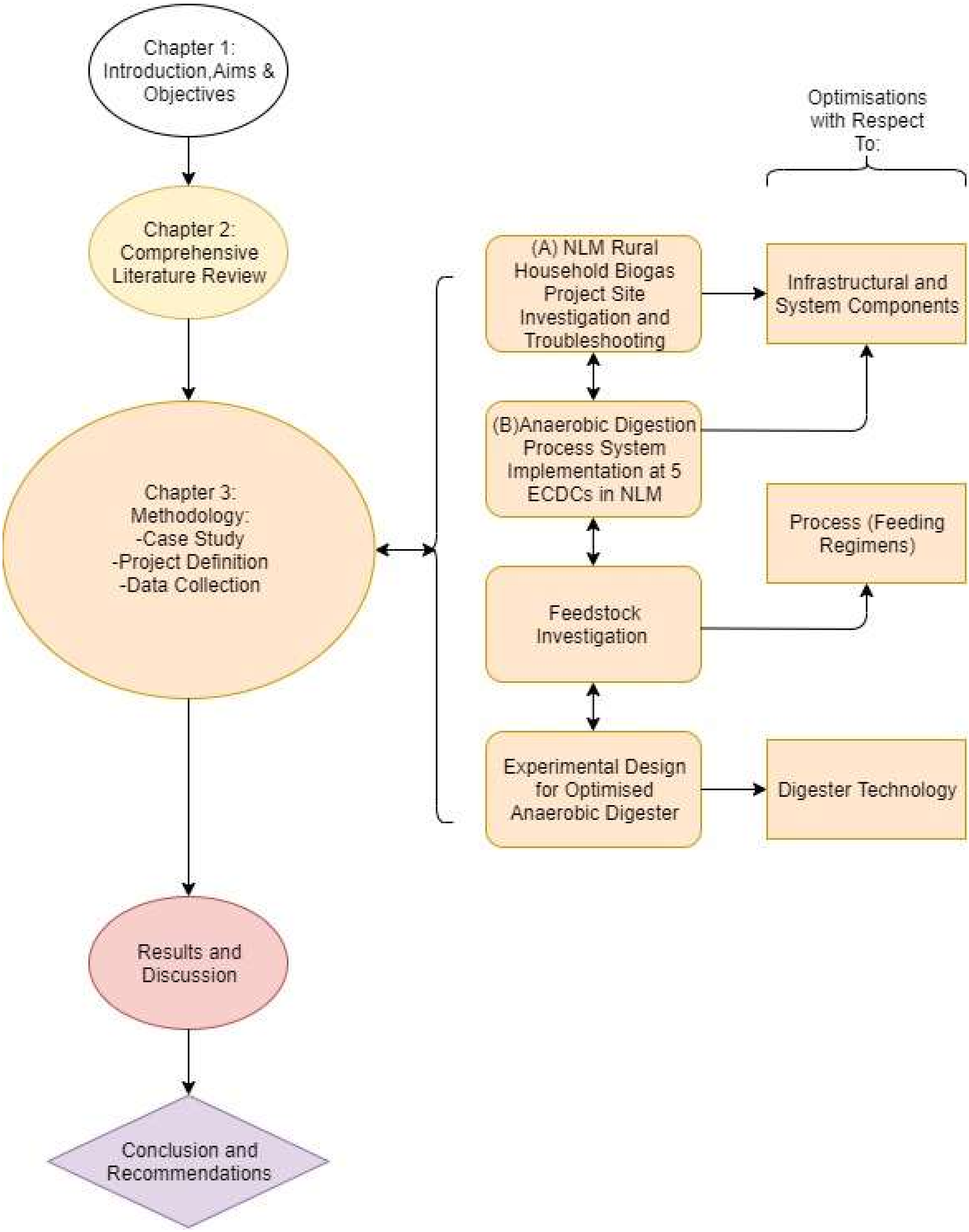

Figure 1-1: General Research Layout

2. LITERATURE REVIEW

2.1. Introduction

This chapter provides a review of current available literature relevant to the study from different authors. The current issues regarding the waste management, energy poverty and the state of biogas in rural South Africa have been discussed. The main aim of this research is to contribute to the development of a best practice model for anaerobic digestion in terms of its process, the digester technology and the infrastructural components. Consequently, this chapter comprehensively reviews the aspects of anaerobic digesters and their different applications, the process of anaerobic digestion, factors that affect the process as well as various other aspects that contributed to the development of this study.

2.2. Waste Management in Rural South Africa

South Africa, like many developing countries, has experienced a rapid increase in population coupled with urban and rural development, changes in lifestyle and subsequent changes in household consumption patterns. These momentous changes in the spatial arrangement and livelihoods of ordinary South Africans has contributed to a number of challenges associated with waste generation and its proper management that require urgent redress.

Sanitary management of domestic waste in rural settings has received minimal attention within developing countries as the concept of sanitary waste management is not sufficiently developed, which necessitates the development and implementation of simple but comprehensive waste management plans (Qarani et al, 2011). Moreover, rapid economic growth and the associated improvements in living standards have contributed to mass consumption and production as well as the improper disposal of waste generated from rural domestic households. This situation is exacerbated by the fact that 61% of South African households have access to kerbside waste collection systems as of 2007, though access to waste management services remains highly skewed in favour of the more urban populace (Department Of Environmental Affairs, 2012). This justifies a need for sanitary, integrated waste management systems for rural areas in South Africa. In addition, this fits into the country's "National Waste Management Strategy" projected goal of the provision of systems to 100% of rural households by 2020 (Department Of Environmental Affairs, 2012).

2.3. Poverty and Energy in Rural South Africa

Boardman and Kimani (2018) have demonstrated that there usually exists a correlation between poverty level and lack of affordable and adequate energy services. This relationship reconstructed a cycle, whereby the affected people are often stuck in a revolving circle characterised by lower incomes, deprivation and the means to upgrade their standard of living while at the same time utilising significant sums of their limited income on expensive or unhealthy energy forms that provide unsafe and/or poor services (Boardman and Kimani, 2018).

According to Johansson et al. (2012), a notable contributor to poverty in developing nations especially in sub-Saharan Africa is the limited access to sustainable and affordable energy services. Therefore, in order to promote economic development, employment opportunities, overcome poverty and generally promote sustainable human progress, it is necessary to provide access to modern energy services to all people without exception; Mbewe (2018) suggests this as one possible solution.

The lack of affordable modern energy services has implications on economic and agricultural productivity, income generation opportunities, and generally the ability to improve standards of living (Vermaak et al., 2009). Low agricultural and economic productivity coupled with skewed livelihood opportunities results in malnourishment, low earnings, and lack of surplus capital. This causes the poor to remain poor, further resulting in an inability to afford cleaner or more sustainable energy services (often neither the equipment nor fuels). The problem of poverty is connected to the lack of cleaner more sustainable energy sources (Vermaak et al., 2009), thus the concept of energy poverty.

2.4. Energy Poverty in Rural South Africa

Vermaak et al. (2009) defines energy poverty as the lack of access to modern energy services. This has led to the development of the “Theory of Transition” which basically describes a trend of households ascending an “Energy ladder” (Vermaak et al., 2009). The ladder begins with traditional biomass fuel sources such as firewood and charcoal, through to transition fuels such as kerosene, and finally to modern commercial fuel sources like electricity. Urbanisation and income rise as the ladder is ascended which implies that a higher energy demand is dictated by an increase in income (Figure 2-1, below).

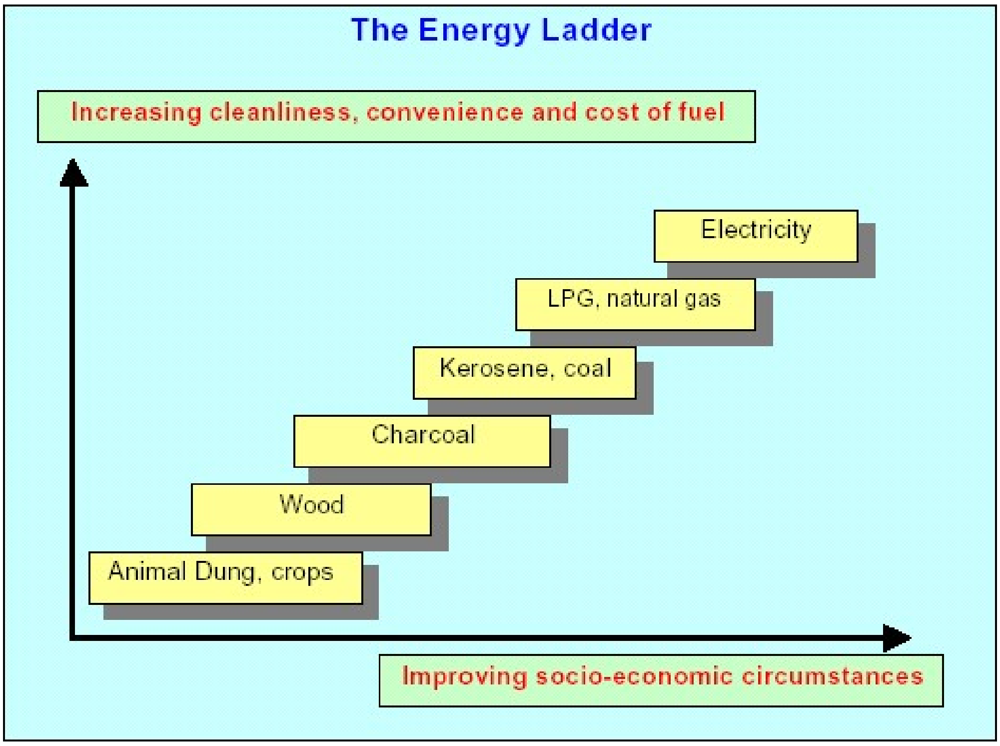

Figure 2-1: The energy ladder (Rwiza, 2009).

The transition to more modern energy services is not easy for most South African families within rural households (Mbewe, 2018). Though records from the Department of Energy (2015) show that South Africa has achieved a commendable 85% household rate of electrification through the national energy supply body, Eskom, it is estimated by the Department of Energy that approximately 45% of households still lack access to modern energy services. Furthermore, according to General House Statistics South Africa (2017), a majority of the energy poor households are heavily reliant on unclean energy sources (Mbewe, 2018). This shows that high rates of electrification do not necessarily reduce energy poverty if households are not able to afford electricity services, especially with respect to low-income populations which are dominant in rural areas as suggested by Mbewe (2018). Decentralised renewable energy technologies could provide a solution to energy poverty in South Africa.

2.5. Renewable Energy Sources in Rural South Africa

According to Aitken et al. (2018), it is estimated that up to three million households in South Africa do not have access to modern energy services. Most of these households are in rural areas and much of the rural populace do not have access to modern energy. Aitken et al. (2018) suggest that addressing this issue requires a different approach which includes “off grid” energy solutions using renewable sources. Renewable energy sources currently available within South Africa include: wind, biomass, solar, and biogas (Pegels, 2010). There have not been many rewarding experiences with renewable energy in South Africa. The most significant decentralised renewable energy programme is the “Off-Grid Concession Programme” which were mainly solar energy interventions. Aitken et al. (2018) performed a study on local and international decentralised renewable energy solutions and the study identified a number of challenges. Successful implementation of a renewable energy project in South Africa revolves around five main challenges which include commercial, technology, innovation, policy and communication issues, as identified by several authors such as Aitken et al. (2018). In order for South Africa to enhance the sustainability and contribution of these energy services, it needs to address these challenges so it can benefit from the obvious advantages of decentralised renewable energy (Jain and Jain, 2017).

The theoretical advantages of the renewable energy like biogas in the rural context would among others include reduced biomass consumption, lower indoor pollution, as well as lower energy costs depending on the financial model (Aitken et al., 2018).

2.6. Biogas as Renewable Energy Source in Rural South Africa

An anaerobic digestion process system refers to a set of components working together to produce biogas for a user (Rogoff and Screve, 2019). The use of biogas as a waste management solution and an alternative energy source has been developed and promoted successfully in many developing countries, particularly in Asia (Bond and R. Templeton, 2011). Biogas in South Africa, like many African countries, has seen limited development which has been attributed by Bond and R. Templeton (2011) to limited research. The underdevelopment of biogas technology in South Africa can also be attributed, Parawira (2009), to a less significant priority given to the technology attributable to various challenges such financial inadequacy and inadequate effort to promote the technology. Sections 2.5.1 and 2.5.2 describe the advantages of biogas technology and the challenges associated with its dissemination identified within literature.

2.5.1. Advantages of Biogas Technology for Rural Areas

According to Msibi and Kornelius (2017), in addition to providing a renewable, free, and clean energy, biogas can create jobs for people since human input is required to implement anaerobic digestion process systems. Humans are required for construction and maintenance of anaerobic digestion process systems and thus can be employed during biogas projects especially for state sponsored interventions (Gautam et al., 2009).

The process of anaerobic digestion provides a bi-product referred to as digestate which can be used as a fertilizer for rural small scale vegetable production. The fertilizer provides organic nutrients to the soil which increases crop productivity (Surendra et al., 2014).

Biogas can contribute to social development through workload reduction for children and women who form the main part of the labour force in a typical domestic rural setting in addition to the reduction in time spent during firewood collection (Ferrer et al., 2011). This improves the development of rural communities.

Bond and R. Templeton (2011) have demonstrated that biogas technology contributes to the decrease in global anthropogenic methane emissions by almost 4%. Therefore, biogas technology contributes to the reduction of greenhouse gas (GHG) emissions, including those related to the burning of firewood and fossil fuels which include paraffin (Ferrer et al., 2011)..

Anaerobic digestion contributes to the reduction of greenhouse gases. Deforestation associated with fuel wood can be reduced by use of biogas technology. According to Ferrer et al. (2011), worldwide deforestation contributes to between 17 and 25% of all anthropogenic GHG emissions through burning of wood. In addition to this, deforestation leads to soil erosion which also comes with a number of adverse effects (Surendra et al., 2014). Furthermore, biogas technology can reduce emissions from livestock manure (Surendra et al., 2014).

2.5.2. Challenges Associated with Dissemination of Biogas Technology for Rural Areas

The challenges associated with the development and promotion of biogas in rural areas in South Africa can be introduced by the absence of a renewable energy policy; Msibi and Kornelius (2017) have shown that currently, there exists no policy on renewable energy especially for biogas. Many of the policies that are used to regulate biogas are derived from other codes, for example the NERSA gas act which was mainly developed for Liquefied Petroleum Gas (LPG). Development of a renewable energy policy would aid in breaking barriers for promotion and dissemination of biogas technology. A national policy can direct participants in maintaining quality of the biogas technology assembly and services (Surendra et al., 2014).

Limited knowledge of biogas technology prevents its adoption by people especially in rural areas. Lack of sufficient knowledge and technical skills of biogas setup, maintenance and daily operation is a major contributor to the failure of biogas projects in South Africa and many African countries (Amigun et al., 2011).

Limited income in rural areas hinders implementation of biogas systems which require financial input that most of the rural populace is unable to afford (Surendra et al., 2014). Research is required to come up with more affordable biogas technology besides cost subsidy by the South African government to improve affordability by the rural poor (Aitken et al., 2018).

Limited availability of water; most anaerobic digesters especially for rural areas are dependent on water to perform satisfactorily (Mengjie, 2002).Drought has started to affect water volume and supply in South Africa (Thorn, 2010). Therefore, lack of water will have an effect on biogas installations in South Africa however the water shortage can be alleviated through the use of grey water that is in plenty as approximately 75% of water supplied in South Africa is greywater (Carden et al., 2007).

Climate affects the temperature within an area. According to Gerardi (2003), temperature is an important parameter that affects anaerobic digestion; generally, warmer temperatures are preferred for anaerobic digestion. According to Thorn (2010), most of South Africa experiences average temperatures below 20 °C. Anaerobic digestion can still occur at such temperatures however it will not be reliable; the lower the temperature, the longer it takes to generate biogas and therefore longer retention times are needed which result in the requirement of bigger reactors which cost more money (Gerardi, 2003).

2.7. Introduction to Biogas Digester Designs

Biogas is a mixture of gases generated as a result of the process of anaerobic digestion which happens in an anaerobic digester (Kougias and Angelidaki, 2018). An anaerobic digester is an airtight container which facilitates the process of anaerobic digestion of biodegradable waste (Kumar et al., 2015). Two main types of digestion can be achieved, dry digestion and wet digestion, which only differ by the fact that water is not added to the waste in dry anaerobic digestion (Hamilton, 2017).

There are three operational modes of anaerobic digesters: passive, low rate, and high rate systems. Passive systems involve the addition of biogas recovery to an existing waste treatment plant with little control of the process of anaerobic digestion, for example a covered lagoon system. Low rate systems involve waste passing through a digester and exiting after the retention time has been lapsed. Examples of low rate systems include complete mix digesters, which involve heating and mixing of the digester content, and plug flow digesters which involves waste entering a digester and displacing an equal amount of material out. High rate systems on the other hand are systems where the microorganisms are trapped in the digester to increase efficiency, for example an up flow anaerobic sludge blanket digester (Hamilton, 2017).

In terms of the process of anaerobic digestion, digesters can be configured to be one stage or two stage digesters (Demirel and Yenigün, 2002). One stage digesters are able to facilitate all the stages of anaerobic digestion in one reactor, while two stage digesters separate the two main processes involved. (Demirel and Yenigün, 2002) have proved two stage digester systems to be more efficient in terms of process stability and biogas yield; however these may require more input in terms of cost to maintain the required optimal conditions of each stage of digestion.

According to Mutungwazi et al. (2018), anaerobic digesters can be categorised, in terms of scale, as domestic digesters, medium commercial digesters, and large scale digesters which have a power supply capacity of less than 25Kw, between 25 and 250 Kw and above 250Kw respectively, dependent on the availability of feedstock. The larger a biogas plant, the more expensive it will be to implement, therefore when planning a set-up, one must consider the law of economy of scale.

2.8. Economies of Scale for Biogas Production

According to Athanassiou (2015), the laws of economy of scale apply when the mean total cost of production reduces as the level of production increases. For example, using a biogas digester to supply gas for cooking for a school of 100 children would have a shorter pay-back period than if the same size digester was used for a household to replace LPG.

Biogas production is associated with economies of scale in operational and capital expenses and diseconomies of scale from transportation of feedstock (Skovsgaard and Jacobsen, 2017). A study done by Skovsgaard and Jacobsen (2017) in Denmark revealed that the benefits of scale in operational and capital costs dominates the diseconomies of scale associated with transportation of feedstock. In addition, the study demonstrated that an increased economy of scales of biogas provision is associated with higher managerial and operational capacity. Operation and maintenance of anaerobic digestion process systems is very important for successful biogas provision (Skovsgaard and Jacobsen, 2017).

2.9. Main Designs of a Small Scale Anaerobic Digesters

At its most basic iteration, anaerobic digester is a sealed oxygen free tank that facilitates anaerobic digestion (Sasse, 1988). A typical digester requires and inlet and an outlet for the substrate to enter and exit the digester after it has been digested (Persson et al., 1979). The digester itself must consist of a headspace for the gas to be stored inside the reactor and a gas outlet to release the produced gas (Persson et al., 1979). The most common and basis of most anaerobic digester designs is the Chinese Fixed Dome Digester(CFDD) which is shown in Figure 2-2 (Cheng et al., 2014). Other main digester typologies that form the basis of most designs are the floating drum digester and the bio-bag digester (Cheng et al., 2014).

The CFDD is designed such that waste enters through the inlet tank and is channelled down to the reactor chamber through an inlet pipe (Persson et al., 1979) (sometimes, the CFDD is designed without using pipes by designing the digester with the inlet tank directly merged to the reactor chamber). As gas is produced in the reactor chamber, it is stored in a gasholder and exerts a pressure on the substrate such that it is displaced into the expansion chamber thus providing pressure to the gas which is dependent on the level of displaced substrate in the expansion chamber (Persson et al., 1979). With reference to Figure 2-2, the parts have been labelled on the CFDD as follows: inlet tank (1), inlet pipe (2) expansion chamber tank (3), gasholder (4), gas pipe (5), entry hatch (6), with gastight seal (7), reactor chamber (8), outlet pipe (9) and supernatant scum (10).

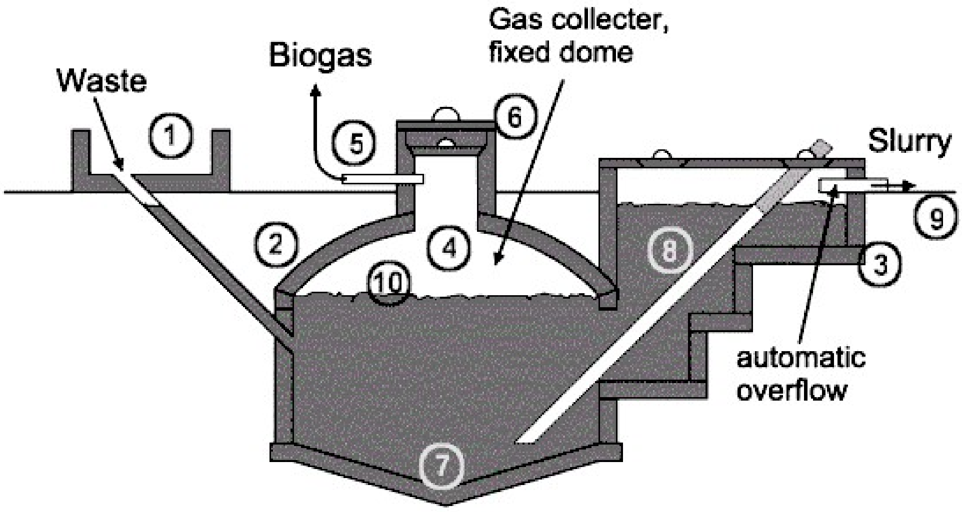

Figure 2-2: Chinese Fixed Dome Digester (Cheng et al., 2014).

The Floating Drum digester on the other hand though similar to the CFDD differs in that it consists of a moving gas holder which floats directly on the substrate in the digester or in its own water jacket, see Figure 2-3. The purpose of the floating drum is for it to provide a constant gas pressure as gas exits the digester (Sasse, 1988).

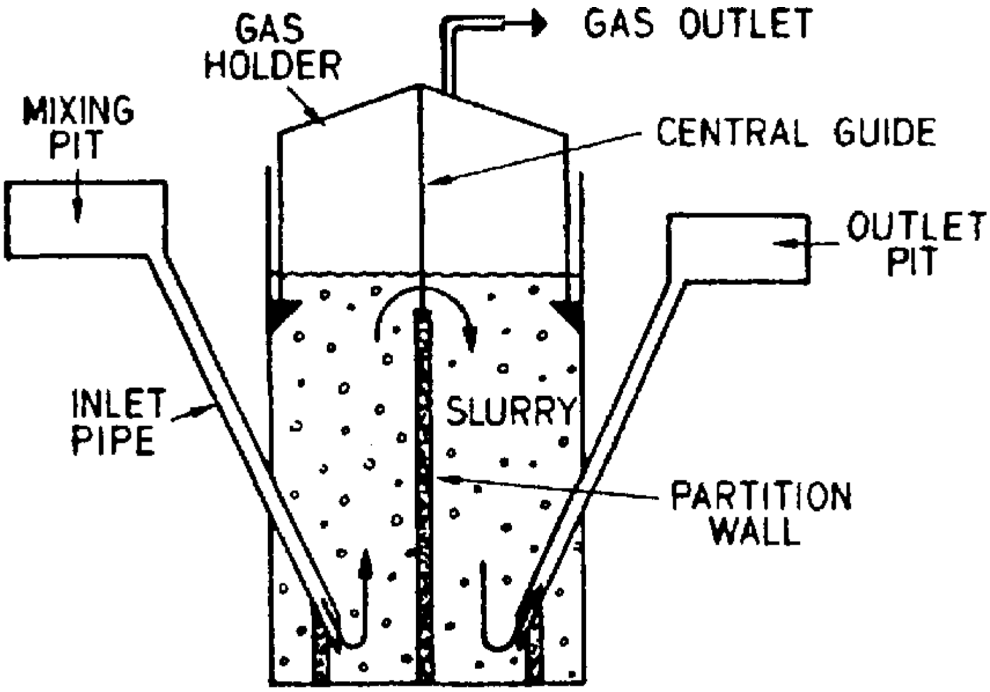

Figure 2-3: The floating drum biogas digester (Sasse, 1988)

Lastly, the biobag digester operates as a plug-flow digester system where the substrate is fed semi-continuously into an inlet pipe and then displaces an equal amount of slurry through an outlet pipe from the digester (Figure 2-4) (Sasse, 1988).

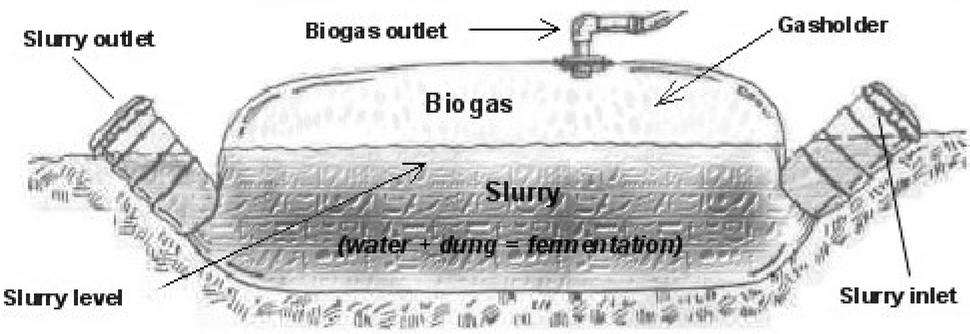

Figure 2-4: The Bio-Bag Digester (Sasse, 1988)

The basis of operation of the three main digester types has been described briefly. These three digester types form the basis of design of most of the other types of digesters that exist in South Africa including prefabricated digesters which are derived from the three aforementioned digester types (Cheng et al., 2014). Table 2-1 describes the advantages and disadvantages of each of these three main digester types.

Table 2-1: Advantages and Disadvantages of Main Digester Types (Cheng et al., 2014)

Digester Type	Advantages	Disadvantages
CFDD	•Long Lifespan •Agitation occurs during gas usage and production •Can easily be prefabricated •Can be constructed using local labour and materials •Can be of $6m^3$-$124m^3$ volume	•May have fluctuating gas pressure depending on design •Brick and mortar designs may be susceptible to leaks during construction •Brick and mortar design is difficult to repair in case of leaks •Limited agitation.
Floating Drum	•Constant gas pressure •Height of drum indicates available gas volume	•Drum affects lifespan since it may require maintenance •Drum may be expensive and difficult to obtain •Construction may be complex •Limited agitation.
Bio-Bag	•Simple and quick to install •Transportable •Lowest cost of installation	•Variable gas pressure •Easily damaged •Difficult to clean •Short lifespan •Limited to low maximum volume of $6m^3$ •Difficult to repair in case of damage •Limited mixing.

The CFDD can be seen to be the most suitable for a rural setting based on its ease and relatively low cost of construction, maintenance and operation. According to the World Health Organization (2019), rural areas are characterised by low educated people who do not possess skills to maintain biogas systems, therefore, systems that require low human interaction and maintenance are more suitable. The bio-bag is a promising option, considering its low cost, however, it may not be a sustainable option since it is susceptible to damage and will require maintenance which may not suit a rural populace.

Many designs of anaerobic digesters exist around the world today, however, according to Sasse (1988), they share a number of commonalities and can typically be assessed on a shared set of criteria. Epp et al. (2008) emphasises the importance of certainty of the source and quantity of feedstock and further emphasises that the maximum radius of feedstock supply should not be more than 5km. In addition, the quantity of feedstock should be enough to meet the required energy requirements. According to Epp et al. (2008) , a digester is designed according to certain main criteria which include but not limited to; cost of the digester, process of anaerobic digestion in the digester, durability, operation and maintenance and finally compliance with relevant design codes; these criteria are often interlinked and interdependent.

2.10. Structural Design of a digester

The structure of an anaerobic digester plays an important role on the strength, cost and durability of an anaerobic digester and, to an extent, the operation and maintenance aspect. (Epp et al., 2008). Therefore, the structural design of a digester should be carefully considered.

Above ground, a digester should be able to resist the maximum forces exerted on it by the substrate in the digester as well as the effect of chemical decomposition as a result of environment or the substrate itself (Sasse, 1988) Underground digesters however need to be designed to resist the forces exerted on it by the ground itself and therefore they should be checked against the forces of the ground at worst case scenario when the tank is empty (Anchor, 1981) An anaerobic digester structure can be designed in many shapes, which affects its structural strength, especially if the digester is to be placed underground. Different shapes have different stress arrangements under then same loading. For instance, cylindrical or rounded shaped digester structures are preferred over rectangular ones, for underground purposes, because they have less stresses acting on them. Figure 2-5 shows how rounded(a) shapes have less stresses than angular ones(b) under the same load as well as how loads acting in different directions are more reliably balanced with a vaulted shape(c) than a vertical wall(d).

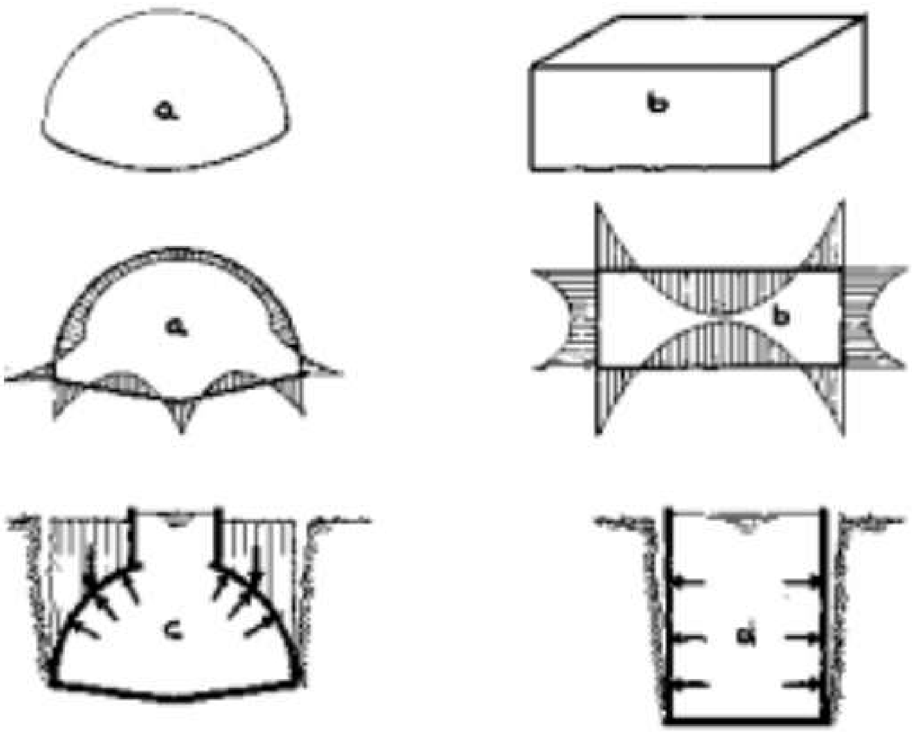

Figure 2-5: Difference in stresses associated with the shape of a digester (Sasse, 1988)

The structural cost of a digester is directly proportional to the cost of material used and the size of the digester. The size of the digester depends on the demand for the gas produced, with larger digesters being able to produce larger quantities of gas (Epp et al., 2008).

2.11. Anaerobic Digester Structural Material

Materials used to design the digester include plastic materials, fibreglass, brick and mortar, steel and concrete (Cheng et al., 2014). The choice of material is dependent on its characteristic strength and the cost (Sasse, 1988). The type of material used for an anaerobic digester is very important as it governs the structural strength and performance of the digester. The material contributes to the performance of the digester because it will govern the ability of the digester to retain heat and the specific parameter which governs this ability is the co-efficient of thermal conductivity (Incropera and DeWitt, 2002). The thermal conductivity is referred to as a transport property that provides an indication of the rate at which energy heat energy is transferred through matter (Incropera and DeWitt, 2002). It is important to minimise heat losses in an anaerobic digester (Gerardi, 2003). Cheng et al. (2014) suggests this as one of the reasons why fibre glass is a material that is used to fabricate domestic anaerobic digesters however concerns may arise due to fibre glass being a brittle material.

Various plastics can be used for the structural design of an anaerobic digester which include PVC (polyvinyl chloride), neoprene, HDPE (high-density polyethylene), PVC (polyvinyl chloride), LDPE (low-density polyethylene), LLDPE (Linear Low-Density Polyethylene) and PE (polyethylene) (Cheng et al., 2014). According to (Rotter and Sadowski, 2016), the structural strength of a plastic digester structure is dependent on the thickness, type of section (rectangular or circular), but most importantly, the material physical and mechanical properties for example compressive and tensile strength. Concrete as well as brick and mortar are popular due to their diverse availability (Rotter and Sadowski, 2016). Table 2-2 shows some typical properties of materials commonly used in the design of anaerobic digesters.

Table 2-2: Properties of common materials used for structural design of anaerobic digesters

Material		Ultimate Tensile Strength (KN/m^2)	Compressive Strength (KN/m^2)	Co-efficient of thermal conductivity (W/m.K)
Plastics[1]	LDPE	8480-26,200	9650*	0.33-0.4
	LLDPE	7300-42,000	12500*	0.32-0.4
	HDPE	23,000-29,500	31700*	0.35-0.49
	PVC	3740-55,900	7.58-6790	0.16-0.19
Fibre-Glass[2]		200,000-400,000	480,000*	0.04*
Brick and Mortar[3]		280-2100	4390-7000	0.6-0.8
Concrete[4]		1400-2800	1400-43000	0.1-0.3

**-Denote average values*

[1] Properties of plastics can be further elaborated in the *Applied Plastics Engineering HandbookDeArmitt C (2011) Applied Plastics Engineering Handbook. pp.455-468.*

[2] Properties of plastics can be further elaborated in *Chapter 5 - Fiberglass tanks* by Cheremisinoff NP and Cheremisinoff PN (1995) Chapter 5 - Fiberglass tanks. In: Cheremisinoff NP and Cheremisinoff PN (eds) *Fiberglass Reinforced Plastics*. Park Ridge, NJ: William Andrew Publishing, pp.138-157.

[3] Properties of brick and mortar can be further elaborated in the *Building Contractors Pocket Handbook* by Clay Brick Association (2018) Building Contractors Pocket Handbook.

[4] Properties of concrete can be further elaborated in the *Fundamentals of concrete book* by *Owens G, Cement and Concrete I (2013) Fundamentals of concrete. Midrand, South Africa: Cement and Concrete Institute.*

2.12. Anaerobic Digestion Process System Implementation and Project Management

As mentioned earlier, an anaerobic digestion process system comprises of a number of components. The components enable the biogas to be conveyed from the digester to the user. Typical components of an anaerobic digestion process system include, but not limited to: sewer, water supply as well as operation and monitoring systems. These components require management in order for them to be implemented at site. Management of biogas projects demands many coordinated activities with varying durations and involves numerous dependencies (Zareei, 2018). Poor management of these activities can cause failure of a biogas project in terms of delayed construction, defects, to mention but a few.

Lean project management can be used to optimise the management of biogas projects. Ballard and Howell (2002) define lean project management as the application of lean manufacturing principles to engineering project management practice. The main aim of lean project management is to minimise waste while maximising value. Ballard and Howell (2002) refers to waste in this context as wastage due to: transportation, inventory, motion, waiting, overproduction, defects and unnecessary workforce.

2.13. Anaerobic Digester Types installed in South Africa

Around 700 digester installations currently exist in South Africa (Mutungwazi et al., 2018). The first anaerobic digester in South Africa was installed on a pig farm in 1957 by John Fry and in 1958, electricity was generated from the plant and was used to power pumps. Since then, many digesters have been installed in the country, however market penetration has been slow compared to similar context such as Brazil, India or China. Table 2-3 presents a list of the recorded biogas digesters that have been installed in South Africa as well as the location, developer name, substrate input and power output.

Table 2-3: List of bio digesters installed in South Africa (Mutungwazi et al., 2018).

Area	Developer	Substrate input	Power output
Alice, Eastern cape	CAE / University of Fort Hare	4000 m3 of dairy and piggery manure	2 × 132 kVa electricity
Athlone Industria	Alrode brewery ,Farm Secure Energy, Wastemart, CEA/New Horizon waste to energy	400 t of organic waste per day	-
Bela-bela Limpopo	CAE Humphries Boerdery piggery	-	-

Area	Developer	Substrate input	Power output
Belville		Waste water treatment plant	
Bonnievale	FarmSecure Carbon	> 5 t bovine manure	
Bredasdorp	iBert	4 t abattoir waste per day	100 kW
Cavalter	iBert	20 t abattoir waste per day	500 kW
Cavalter	EnviroServ/ Chloorkop LFG	-	-
Cavalter	Cullinan	-	190 kW
Darling Uilenkraal	CAE/Uilenkraal dairy farm	Bovine manure	600 kW
Darling GrootPost	FarmSecure manure	Bovine manure	-
Durban	Bisasar road LFG	3500–5000t refuse per day	6 MW
Durban	Marrianhill LFG	550–850 t per day	1.5 MW
Durban	Ekhurleni LFG	-	-
Grabouw	Elgin Fruit and juices Ibhayi brewery	> 5 t of fruit waste per day	500 kW
Jan Kempdorp	iBert	5.5 t abattoir waste per day	135 kW
Jan Kempdorp	Jacobsdale	-	150 kW
Johannesburg	WEC/Northern Waste Water Treatment Works	Sewage sludge	1.2 MW
Johannesburg	Robinson Deep	-	19 MW
Klipheuwel	Reliance Composting	700 t organic waste per day	
Klipheuwel (Zandam)	Farmsecure	> 5 t of manure per day	600–700 kW
Mossel Bay	Biotherm SA, Mossel Bay PetroSA	Refinery waste water	4.2 MW
Newlands	SAB Miller	4500 m3 of wastewater per day	10% of the plant’s energy
Paarl	Drakenstein Municipality	-	14 MW
Pretoria	Bio2watt / Bronkhorst-Spruit Biogas plant	Manure	4.6 MW
Pretoria	Prospection brewery		
Queenstown	iBert	42 t mixed waste from a piggery per day	
Riverdale	iBert	4 t abattoir waste per day	100 kW
Riverdale	Robertson	-	150 kW
Riverdale	Rosslyn brewery	-	
Springs	BiogasSA / Morgan Springs Abatrtoir	Slaughter waste and organic waste	0.4 MW
Stellenbosch	Veolia water Technologies / Distell	1000 m3 wastewater per day	-
Stellenbosch Franschhoek	Rhodes Food Group	35 kg per day(testing feedstock)	-

Area	Developer	Substrate input	Power output
Stellenbosch Franschhoek	Selectra	Sewage, silage, manure	0.5 MW
Stellenbosch Franschhoek	Selectra	Sewage, silage, manure	1 MW
Stellenbosch Franschhoek	Selectra	Sewage, silage, agricultural waste	1 MW
Table view	Jeffares and Green / Bayside Mall	0.6–1 t of food waste per day	
KZN	Khanyisa projects	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
KZN	SANEDI	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
EC (Alice, Fort Corx and Melani villages), WC, (pHillipi), KZN	AGAMA	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
Gauteng	Zorg	Vegetable pulp + silage plant	7200 m3 methane

Three projects have been principally responsible for the installation of the majority of domestic anaerobic digesters currently installed in South Africa; namely: The Melani village biogas expansion, Mfuneko and Illembe district projects. The majority of domestic anaerobic digesters have been installed through SANEDI's "Working for Energy Programme" (described in Chapter Three). There are a number of active developers in the small scale digester sector including AGAMA and BiogasSA (Mutungwazi et al., 2018). All these digesters have different designs that all have their individual advantages and disadvantages.

2.14. Comparison of Anaerobic Digester Types Installed in South Africa

Domestic digesters are installed for direct gas use rather than electricity generation and are installed on a small scale for example at households, small schools or small farms (Mutungwazi et al., 2018). Domestic digesters are the most common in South Africa and they can be used for cooking, lighting and sanitation (when used as part of an integrated system). The different developers of domestic digesters have produced different designs which have been assessed and summarised in the Table 2-4 below.

Table 2-4: Comparison of different digester designs in South Africa

Name Of Digester	Developer	Size	Material	Advantages	Disadvantages
AGET 10m3 digester	Africa green energy technologies	$10m^3$	Concrete	•Consistent pressure since biogas is stored in biobag •Portable •Does not require excavation	•Lack of agitation •Dependant on ambient temperature
AGET 2.5m3 digester	Africa green energy technologies	$2.5m^3$		•Consistent pressure since biogas is stored in biobag •Portable •Does not require excavation	•Lack of agitation •Dependant on ambient temperature
AGAMA prefabricated fixed dome digester	AGAMA	$6m^3$	LLDPE	•Long lifespan of more than 20 years •Consistent gas pressure •Portable with quick underground installation •Uniform temperature since it is installed underground	•Lack of agitation •Requires excavation
EZ floating drum digester	Biogas SA	$1.5m^3$	Polyethylene	•Does not require excavation •Comes with insulation blanket	•Lack of agitation •Dependant on ambient temperature
Little green monster digester (CFDD)	Pioneer Plastics Energy	$2.5m^3$	PVC	•Requires excavation	•Lack of agitation •Dependant on ambient temperature •Not structurally reliable
Puxin fixed dome digester	Shenzhen Puxin Science and Technology Company	$10m^3$	Concrete	•Relatively long lifespan •Uniform temperature since it is installed underground •Construction materials are easily attainable •Construction can be done easily using shutter system[5]	•Lack of agitation

[5] More information about this construction technique can be found at http://www.biogassa.co.za/index.php/sa-biogas-projects/small-scale

A review of the bio-digester technologies in South Africa reveals that their suitability is dependent on strength, cost, availability of materials and ease of operation and maintenance according to Mutungwazi et al. (2018). Mutungwazi et al. (2018) found the Puxin digester to be the most suitable digester type in South Africa based on its design that eliminates the limitations of the CFDD and floating drum digester. The conclusion was reached after a realisation of its ease of construction and operation, constant biogas pressure and its relatively long lifespan. However, the Puxin digester's size makes it infeasible at certain scales, and in addition its construction costs may be high. Therefore, at a smaller scale, the AGAMA 6m^3 digester is the most suitable type of digester since it similarly eliminates limitations of the CFDD and floating drum digester. The price of the AGAMA 6m^3 digester was reported to be high, however, its installation requires minimal labour so it may be an overall cheaper technology to utilise. Furthermore, the price of the AGAMA 6m^3 digester has not changed since its inception which may make it cheaper considering inflation (Ayres, 2016). In addition, according to Ayres (2016), it has been designed (see section 4.5.3.1.) to treat sewage more efficiently. Both designs however have limited agitation and are dependent on the ground temperature for insulation (Mutungwazi et al., 2018).

2.15. Process of Anaerobic digestion

Anaerobic digestion is a natural process that occurs in the absence of oxygen at specific temperatures that involves complex breakdown of organic substrates to yield biogas (Monnet, 2003). The process is facilitated by interactions between diverse microbial organisms which thrive under different specific conditions (Meegoda et al., 2018).

The process of anaerobic digestion to yield biogas is divided into three main stages. These three main stages involved are hydrolysis, acid formation and methane production (Gerardi, 2003) The process of anaerobic digestion proceeds efficiently if the rate at which each stage occurs is equal. If any of the stages is inhibited, then the proceeding stages will not occur because their substrates will be limited and methane production will decrease (Gerardi, 2003). For example, If the third stage is inhibited, the acids formed from the second stage will accumulate too quickly for the proceeding stage.

The anaerobic digestion process is facilitated by numerous groups of specific microbial organisms that complement each other in sequence with the by-products of one microbial group serving as substrates for the proceeding group. Therefore the microbial groups are interlinked in a chainlike fashion with the weakest links being the acetogenic and methanogenic group (Gerardi, 2003).

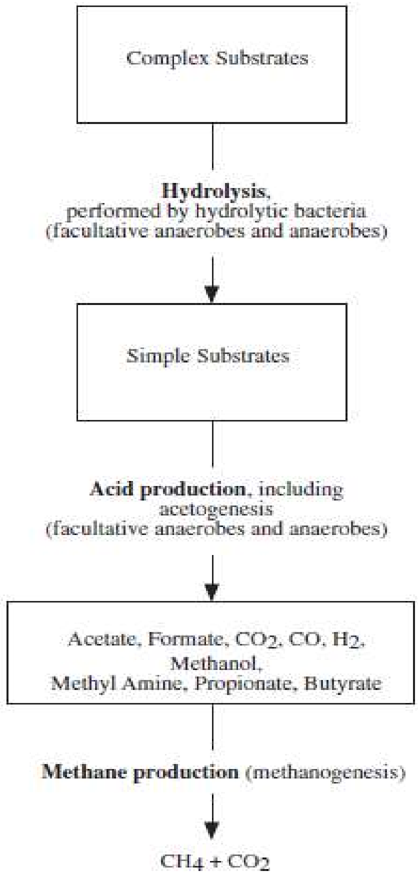

Figure 2-6:Simplified stages of anaerobic digestion

The process can be further split into four main stages which occur simultaneously and synergistically (Meegoda et al., 2018). These four main stages include: hydrolysis, acidogenesis (fermentation), acetogenesis and methanogenesis as, illustrated in Figure 2-7, which, in addition, shows the two main pathways of methane production (acetoclastic and hydrogenetrophic).

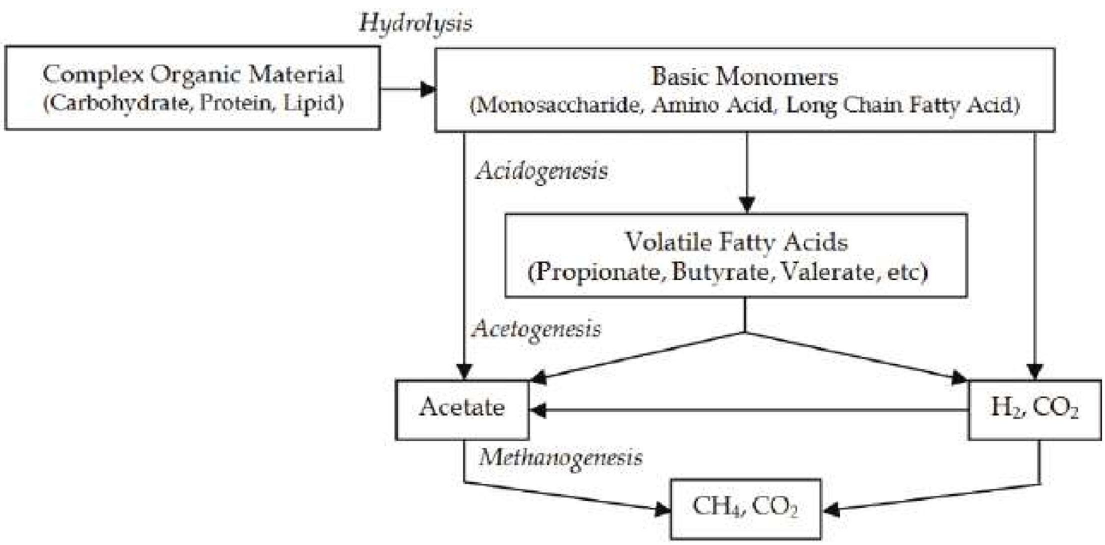

Figure 2-7:Detailed process of anaerobic digestion (Meegoda et al., 2018).

2.15.1. Hydrolysis

The first stage of anaerobic digestion that organic matter undergoes is called hydrolysis. Organic matter contains complex polymers that are inaccessible to the microbial populations and therefore need to be made accessible for all the stages of anaerobic digestion to occur (Meegoda et al., 2018).

Hydrolysis is an electrochemical process but however, it commonly exists as a biological one. The biological process is facilitated by hydrolytic bacteria which release extracellular enzymes that then convert the complex polymers into simple monomers. The proteins ,carbohydrates and lipids are converted into amino acids, simple sugars and long chain fatty acids respectively (Meegoda et al., 2018). After enzymatic fragmentation of the organic matter, the products of hydrolysis are then diffusible through cell membranes of acidogenic bacteria.

Hydrolysis can therefore be the rate determining stage, however, research has shown that methanogenisis could exist as a rate determining step but is dependent on the ratio of methanogenic to hydrolytic bacteria. However, during the degradation of very complex organic matter for example lignocellulosic matter, hydrolysis will be the rate limiting stage (Gerardi, 2003). For this reason, Graef and Andrews (1974) , Demirel and Yenigün (2002) and several other authors have paid close attention towards expediting the process in digester and thus many pre-treatment methods are being researched and used to optimise the process especially for digesters that digest highly lignocellulosic organic matter. Equations 2-1 has presented the hydrolytic metabolic process reactions.

Equations 2-1: Hydrolytic metabolic reactions of carbohydrates, proteins and lipids

Complex carbohydrates → Simple sugars

Complex lipids → Fatty acids

Complex proteins → Amino acids

2.15.2. Acidogenesis

Acidogenesis is a biological process whereby acidogenic microorganisms are able to yield intermediate volatile fatty acids and other products through absorption of the products of hydrolysis through their cell membranes (Meegoda et al., 2018). The exact concentrations of intermediate acids formed during this stage is dependent on the condition of the digester; reports have shown that VFA concentrations can vary considerably depending on the pH within the digester though other studies show seemingly contradicting information (Wu et al., 2010).

In comparison to the other stages of anaerobic digestion, acidogenesis generally occurs at a quicker rate with the acidogenic bacteria having a regeneration period of less than 36 hours (Deublein and Steinhauser, 2011). It is important to note that despite the fact that VFAs create precursors for the methanogenic stage of digestion, VFA acidification may cause digester failure since the pH changes will affect the methanogenic bacteria negatively (Akuzawa et al., 2011).

Lastly, within protein rich waste such as wastewater sludge, it fits to scrutinise the process by which VFAs are produced from amino acids. Amino acids are generally degraded into VFAs in pairs through the Stickland reaction by means of single amino acid degradation which is also possible in the presence of hydrogenotrophic bacteria, though the latter process is known to be a slower one. During the decomposition of amino acids, ammonia is produced from deamination, which at sufficiently high concentrations, will inhibit the process of anaerobic digestion (Akuzawa et al., 2011). Other products of acidogenisis include acetate and alcohols. The metabolic reactions have been presented in Equation 2-2.

Equation 2-2: Acidogenic metabolic reactions

Simple sugars + fatty acids + amino acids → organic acids, including acetate + alcohols

2.15.3. Acetogenesis

Acetogenisis is a biological process whereby acids and alcohols from the acidogenic stage are degraded to acetate that can be used as a substrate for the methanogenic bacteria. The production of acetate through acidogenesis already renders a portion of the original substrate suitable for acetoclastic methanogenisis (Fournier and Gogarten, 2008). However, other VFAs need to be accessible to methanogenic bacteria in order for the process of anaerobic digestion to continue.

Acetogenesis also leads to production of hydrogen gas (Ghosh et al., 2016). The hydrogen gas yielded during this process broaches the discussion of a syntrophic relationship that occurs during anaerobic digestion known as hydrogen interspecies transfer. While acetogenesis leads to hydrogen production, an excessive partial pressure has been proven to be deleterious to acetogenic bacteria (Dinopoulou et al., 1988). However the presence of hydrogenottrophic methanogens enables hydrogen to be rapidly consumed while maintaining the partial pressures at a level that favours acetogenesis by forming an exergonic reaction (Stams and Plugge, 2009).

During this stage of anaerobic digestion, lipids go through a different pathway of Acetogenesis through acidogenesis and beta-oxidation, whereby acidogenesis generates acetate from glycerol and the beta-oxidation generates acetate from Long Chain Fatty Acids (LCFA) (Cirne et al., 2007). It is useful to note that only LCFA with an even number of carbon atoms are able to degrade to acetate while those with an odd number of carbon atoms are first degraded to propionate (Cirne et al., 2007).

2.15.4. Methanogenesis

Methanogenesis, which is defined as the formation of methane by methanogenic microbes, is the final stage of anaerobic digestion which leads to production of methane gas through the consumption of accessible intermediates by microorganisms (Ferry, 2010). The microbial organisms that are directly involved in methanogenisis are the *Archae* (Rosato, 2017).

According to Rosato (2017) the *Archae* kingdom is comprised of two subkingdoms namely: the *Euryarchaeota* and the *Crenarchaeota* kingdoms. The *Crenarchaeota* are known as extremophile organisms because they are typically found in envrionments with extremely high temperatures, salinity values, pressures or pH such as submarine volcanoes, sulphur lakes and saline lakes. The *Euryarchaeota* on the other hand include all methanogenic species that are known to date, which thrive at different temperature ranges, as mentioned earlier. In addition, different methanogenic organisms derive their nourishment from either hydrogen or acetate. Methane production mainly occurs through two reaction pathways that include the reactions that involve acetate (Equation 2-3) as well as the reactions that involve carbon dioxide and hydrogen gas (Equation 2-4), however methane can also be generated from methanol (Equation 2-5) (Ferry, 2010).

Equation 2-3:Acetoclastic methanogenesis

$$\text{Acetate} \rightarrow CH_4 + CO_2$$

Equation 2-4:Hydrogenotrophic methanogenesis

$$H_2 + CO_2 \rightarrow CH_4$$

Equation 2-5:Methyltrophic methanogenesis

$$\text{Methanol} \rightarrow CH_4 + H_2O$$

Therefore, all fermentative products are required to be converted to compounds that can be directly or indirectly utilised by methanogenic organisms. Alcohols, acids and organic nitrogen compounds that do not get degraded by methanogenic bacteria accumulate in the digester supernatant and this contributes to the relatively high organic strength of the supernatant (Gerardi, 2003).

In order for this process to proceed, there must be an equilibrium between the rate of degradation by acid forming and methane producing bacteria (Gerardi, 2003). As the methanogenic stage proceeds, the acids are broken down and slight alkalinity is achieved through the formation of ammonia that is released as protein and amino acids are broken down.

The ammonia that is released tends to react with water and carbon dioxide which then leads to the production of ammonium carbonate which provides alkalinity to the system. The ammonium carbonate is then free to react with the volatile acids in the substrate. This reaction leads to the production of volatile acid salts (Gerardi, 2003).

The decomposition of complex organic compounds to methane is dependent on the rate at which compounds can be converted to substrates that can be degraded by methanogenic bacteria (Gerardi, 2003) Within the anaerobic chemical conversions and degradation of organic compounds, the production of acetate is the rate limiting step in the final degradation of organic compounds. For poorly degradable organic compounds, the hydrolytic stage may be the rate limiting step.

2.16. Introduction to factors that affect the process of anaerobic digestion

The process of anaerobic digestion can be difficult to control in an anaerobic digester (Gerardi, 2003). This is due to the various operational conditions that are often interrelated and variations in any may directly or indirectly affect others.

Methanogenic organisms obtain little energy from the degradation of volatile acids (Ferry, 2010). Due to the low energy yield obtained by methanogenic bacteria, their growth rate is restricted; hence the amount of substrate utilisation with respect to a unit of organisms is high and therefore the growth of these bacteria is slow (Ferry, 2010). The slow growth of these bacteria necessitates maintenance of optimum operational conditions to enable satisfactory rates of solids destruction and methane production.

Methanogenic bacteria are strict anaerobic bacteria are extremely sensitive to variations in temperature, pH and alkalinity (Ferry, 2010) In addition to these conditions, several other operational parameters should be maintained and monitored to accommodate acceptable activity of methanogenic bacteria. Conditions that should be maintained include; gas composition, oxidation reduction potential (ORP), temperature, HRT and volatile acid concentration, while gas composition should be monitored to indicate that state of the biological process. (Gerardi, 2003) The optimal and marginal values of these conditions have been shown in Table 2-5.

Table 2-5:Operational conditions for acceptable activity of methanogenic bacteria (Gerardi, 2003).

Condition	Optimum	Marginal
Alkalinity, mg/l as CaCO3	1500–3000	1000–1500 3000–5000
Methane, % volume	65–70	60–65 & 70–75
Carbon dioxide, % volume	30-35	25–30 & 35–40
Hydraulic retention time, days	10–15	7–10 & 15–30
pH	6.8–7.2	6.6–6.8 & 7.2–7.6
Temperature, mesophilic	30–35°C	20–30° & 35–40°C
Temperature, thermophilic	50–56°C	45–50° & 57–60°C
Volatile acids, mg/l as acetic acid	50–500	500–2000

The presence of different bacterial populations also make the operation of an anaerobic digester complex because the different microbial groups require different optimum values for optimal operation of an anaerobic digester (Gerardi, 2003) For example acid forming bacteria require an optimum temperature of about 30°C, while methanogenic bacteria require about 35°C (Gerardi, 2003).

2.16.1. Temperature

Anaerobic digesters have commonly recurring problems associated with failure to maintain an optimum temperature inside the digester (Kim et al., 2017). The microbial organisms that facilitate anaerobic digestion, especially the methanogenic bacteria ,are very sensitive to temperature changes (Gerardi, 2003). According to Tu et al. (2016), there are four types of methanogenic bacteria, with respect to temperature, namely psychrophiles, mesophiles, thermophiles and hyperthermophiles (as shown in Figure 2-8) that are active in their respective different temperature ranges. Adequate mixing of the digester’s constituents can prevent the formation of localised pockets of different temperature (Gerardi, 2003). Anaerobic digester performance falters during the transitions from the different optimal temperatures for the respective bacteria and therefore it is crucial to prevent temperature variations inside the digester.

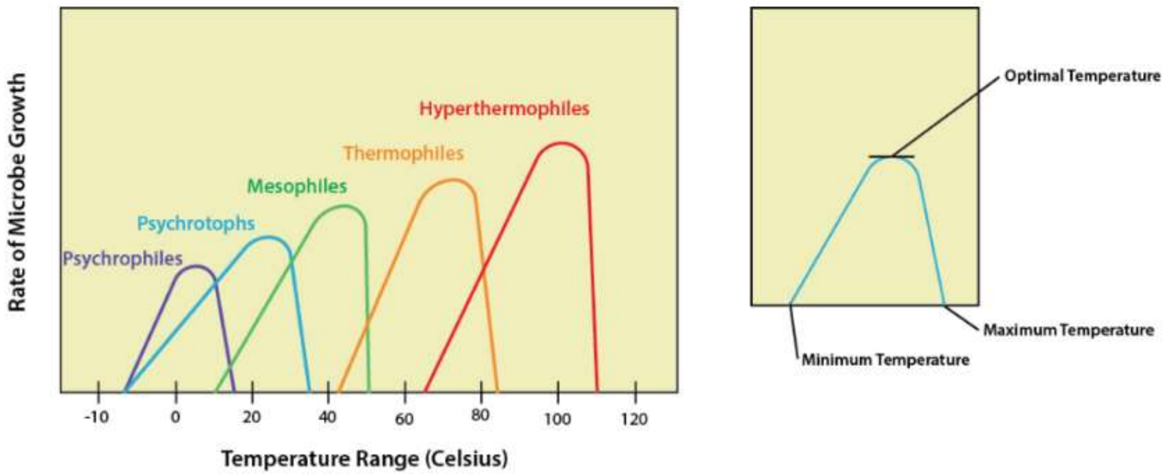

Figure 2-8:Temperature ranges for different types of methanogenic bacteria with respect to temperature (Tu et al., 2016).

Despite the various temperature ranges that can be used to facilitate anaerobic digestion, most anaerobic digesters are mesophilic digesters which are operated at an optimum temperature of about 35°C (Table 2-6). This is because most methanogenic bacteria are mesophilic and the temperature is not as difficult to achieve as thermophilic and still facilitates acceptable performance (Gerardi, 2003).

Table 2-6:Temperature ranges for mesophilic digesters (Gerardi, 2003).

Temperature, °C	Methane Production
35	Optimum
32–34	Minimum
21–31	Little, digester going “sour”
<21	Nil, digester is “sour”

Close attention should be paid to the volatile fatty acid to alkalinity ratio whenever the temperature falls below 32°C. This is because the volatile acid formation will continue at depressed temperatures but methanogenesis will proceed slowly (Gerardi, 2003). Acid production can continue rapidly at temperatures as low as 21°C where as methanogenesis will proceed very slowly and this may inhibit methanogens and this condition in a digester is commonly known as “going sour” (Wang et al., 2019).

Methanogenic bacteria are active and grow in several temperature ranges, but majority of them are mesophiles (Tu et al., 2016). Anaerobic digestion in the psychrophilic range is usually performed in small scale treatment units for example Imhoff tanks, septic tanks and waste water stabilisation ponds (Gerardi, 2003). These units are not heated and the temperature is dependent on the environment and therefore will vary from season to season. The depressed temperature of the system necessitates long retention times.

Thermophilic anaerobic digestion is usually confined to industrial waste water treatment plants that are able to meet the heating requirements (Gerardi, 2003). Table 2-7, below, presents comparative advantages and disadvantages of mesophilic and thermophilic digesters. The efficacy of pathogen destruction in thermophilic anaerobic digestion has drawn attention to its use in satisfying existing and proposed disposal regulations.

Table 2-7: Comparison between mesophilic and thermophilic digestion (Gerardi, 2003).

Feature	Mesophilic Digester	Thermophilic Digester
Temperature control	Less energy intensive	More energy intensive
Loading rates	Lower	Higher
Destruction of pathogens	Lower	Higher
Sensitivity to toxicants	Lower	Higher
Operational costs	Lower	Higher

Although 25% to 50% more activity transpires in thermophilic than mesophilic anaerobic digesters, several microbiological characteristics may adversely affect digester performance (Fournier and Gogarten, 2008). According to Gerardi (2003) these characteristics include; low bacterial growth rate, high endogenous death rates, and the lack of diversity of these microbial organisms. These characteristics could lead to; relatively high residual volatile acid concentration and inconsistent treatment of waste water sludge during continuously fluctuating operational conditions (Gerardi, 2003). As mentioned earlier, thermophilic anaerobes are very sensitive to temperature fluctuations ,therefore constant temperature maintenance is crucial and furthermore, Gerardi (2003) suggests and fluctuations for thermophiles should be less than 1°C for thermophiles and 2-3°C for mesophiles. Temperature fluctuations therefore affect the activity of these bacteria to a greater extent than operating temperature (Tu et al., 2016).

Temperature also has an influence on acid forming bacteria in addition to its effect on methane forming bacteria and therefore temperature fluctuations can favour certain bacteria groups. For example, according to Gerardi (2003), a 10°C temperature increase can stop methane production within 12 hours while acid production will continue to increase.

According to Gerardi (2003) ,the hydrolytic stage of anaerobic digestion is not greatly affected by temperature because hydrolytic bacteria are not as temperature sensitive as the acetate-forming and methane-forming ones. However temperature affects all biological activity in that an increase in temperature results in more enzymatic activity and thus faster rate of biochemical reactions (Gerardi, 2003) Therefore, Solids Retention Time (SRT) within digesters should increase with decreasing temperature due to the effect of temperature on enzymatic activity.

The ability to acclimatise to changes in temperature allows microorganisms to survive or grow at temperatures at or near maxima and minima. Most organisms are able to alter the types of lipids that are being synthesised in response to temperature fluctuations (Tu et al., 2016). In addition, the induction of cold shock or heat shock proteins are general stress responses that include the expression of chaperone proteins; these may assist to fold unfolded proteins or can form protective shells around proteins to protect them from denaturation (Tu et al., 2016). However, despite the ability of methane forming bacteria to acclimate to operating temperature outside their optimum range, digester performance may be compromised because bacteria growth will be slowed while acclimatisation will proceed very slowly (Ferry, 2010).

2.16.2. Organic Loading Rate

The rate at which organic substrates are introduced into the digester is known as the organic loading rate (OLR). It is commonly expressed as the daily quantity of organic matter per unit volume of digester (for example lbVS/ft3/day or kgVS/m3/day) (Gerardi, 2003). In some instances, the organic loading may be expressed using the Chemical Oxygen Demand (COD) rather than the Volatile Solids (VS), especially for liquid substrates. The Chemical Oxygen Demand is defined as the quantity of a specific oxidant that reacts with a sample under controlled conditions (Eaton et al., 2017). COD, similarly, provides an indication of the quantity of organic matter. Unfortunately, there are no strict norms about the units of measurement but to enable comparison between the two, according to Rosato (2017), one can theoretically approximate a correlation between VS and COD for some pure substance according to Figure 2-9[6]

[6] Detailed information on the subject can be found in section 1.2.2.1. of “Managing Biogas Plants” by Rosato MA (2017) *Managing Biogas Plants: A Practical Guide.* CRC Press.

Substance	Chemical Formula	g VS/g COD
Vegetal and bacterial biomasses	≈50% C	1.3333
Glucose	$C_6H_{12}O_6$	1.0666
Sucrose (saccharose)	$C_{12}H_{24}O_{12}$	1.0666
Fructose	$C_6H_{12}O_6$	1.0666
Starch	$(C_6H_{12}O_6)_n$	1.0666
Cellulose	$(C_6H_{10}O_5)_n$	0.84375
Proteins	55% C + 7% H + 17% N + 21% O	≈0.42
Acetic acid	CH_3COOH	0.93
Sodium acetate	CH_3COONa	0.93
Propionic acid	$C_3H_6O_2$	0.6622
Sodium propionate	$C_3H_5O_2Na$	0.6622
Butyric acid	$C_4H_8O_2$	0.5525
Sodium butyrate	$C_4H_7O_2Na$	0.5525
Vegetable oils (assumed as oleic acid)	$C_{18}H_{34}O_2$	0.346

Figure 2-9: Equivalence Ratios between VS and COD of Some Pure Substances (Rosato, 2017)

Links have been established between the microbial community structures and Volatile Fatty Acid (VFA) profiles. If the OLR is too high, the rate of volatile acid production will be greater than their consumption and thus causing a digester failure and at the same time if the OLR is too low, biogas yields will be low (Robert et al., 2016). Possibilities of VFA accumulation exist when an anaerobic digester at a higher OLR with a shorter SRT. Figure 2-10, according to Dennis and Burke (2001), shows the percentage reduction in digester's efficiency with increasing OLR.

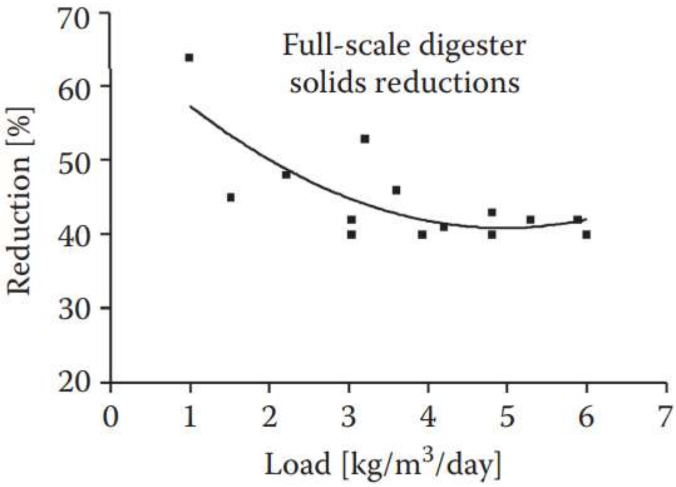

Figure 2-10: Percentage Reduction of Digester Performance with Increase in OLR (Rosato, 2017)

The OLR is essential in that its deliberate variation can determine the degree of digestion for a broad influent input level. According to Chen et al. (2008), higher operating OLR are typically preferred as this enables enriched bacterial species, reduced reactor sizes and enable larger volumes of feedstock to be digested. Several reactor sizes have been investigated to enable higher OLRs (Liu et al., 2017a).

Digester loading may be done as a "batch" or "continuous feed" (Facchin et al., 2013). Batch loading is simply whereby feedstock is added to a reactor for a selected period of time, products are extracted and the reactor is emptied and reloaded. Continuous feeding involves maintenance of anaerobic bacteria in a reactor while feedstock is added at selected intervals. Digesters may also be grouped as high rate and low rate systems which are dependent on the OLR. The CFDD, floating drum and bio-bag digesters, as well as most domestic digesters types, are classified as low rate systems. Figure 2-11, below, shows some OLRs used for some digester types

Criteria	Low rate	High rate contact process	High rate complete mixed	High rate Others
TS (%)	0.5–5	< 5–10	10–15	< 3–5
HRT/SRT (d)	30–60/50–100	>15/30	30	< 20/30–50
OLR	0.5–1.6 (kg-VS.d^{-1}/m^3)	1.6–4 (kg-VS.d^{-1}/m^3)	4–8 (kg-VS.d^{-1}/m^3)	Up to 50 kg-COD d^{-l}/m^3
Solids characteristics	Fine	Fine	Fine	Fine
Capacity range (tons/y)	1–5	-	1,000–230,000	Up to 8,760,000
Heating	None	√	√	Sometime yes
Mixing	None	√	√	None
Level of technology	Low	High	High	High
Water demand	Very high	High	High	
Construction cost	Low	Very high	Very high	High
Maintenance cost	Very low	High	High	High
Equipment invest	Low	High	High	High

Figure 2-11: Characteristics of different digester types with respect to OLR (Van et al., 2020)

Temperature, mixing and retention time conditions govern the loading rate and various approaches of organic loading rate optimisation have been researched many of which are iterative. Samson et al. (2018) describes an example of an iterative process to optimise digester OLR (Figure 2-12).

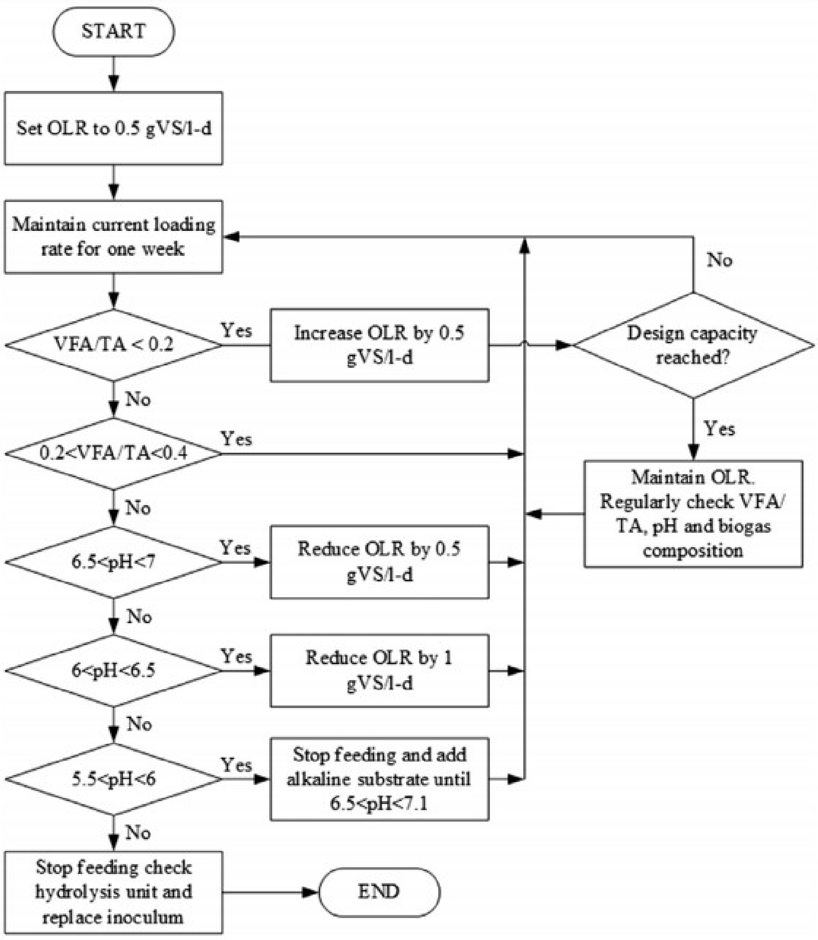

Figure 2-12: Iterative process to optimise OLR (Samson et al., 2018)

2.16.3. Retention Times

Retention time refers to amount of time a substance will spend inside a vessel (Kim et al., 2013). The two significant retention times in an anaerobic digester are the hydraulic and solids retention time (HRT and SRT respectively).

Feedstock to an anaerobic digester comprises of solids and liquids. The time that the entire feedstock spends inside the digester is known as the HRT while that spent by only the solids is the SRT (Gerardi, 2003). The SRT and HRT for a suspended-growth anaerobic digester that does not recycle solids are the same, however, if solids recycling is incorporated in the digester system, then the SRT and HRT may vary considerably (Gerardi, 2003).

Methanogenic bacteria require a relatively long generation time (the time required to double a bacteria population size) in comparison to aerobic bacteria and facultative anaerobes (see

Table 2-8). Typical SRTs for anaerobic digesters are usually greater than 12 days and SRTs of less than 10 days are not recommended because significant loss, through washout, of methanogenic bacteria will occur (Gerardi, 2003). This indicates that SRT is more important than HRT. SRT is not is greatly affected by the characteristics of the feedstock but toxicity in the feedstock could kill the bacteria required to facilitate anaerobic digestion.

Table 2-8:Approximate Generation Times of Important Groups of Wastewater Bacteria (Gerardi, 2003).

Bacterial Group	Function	Approximate Generation Time
Aerobic organotrophs	Floc formation and degradation of soluble organics in the activated sludge and trickling filter processes	15-30 min
Facultative anaerobic organotrophs	Floc formation and degradation of soluble organics in the activated sludge and trickling filter processes, hydrolysis and degradation of organics in the anaerobic digester	15-30 min
Nitrifying bacteria	Oxidation of NH + and NO - in the activated sludge and trickling filter processes	2-3 days
Methane-forming bacteria	Production of methane in the anaerobic digester	3-30 days

High SRTs are beneficial for anaerobic digesters (Gerardi, 2003). High SRTs enable reduced required digester volume, maximised removal capacity and provide buffering capacity for protection against effects of toxicity in feedstock and shock loadings (Gerardi, 2003). High SRTs can be achieved by increasing the size of the digester or increasing the concentration of feedstock solids (i.e. by reducing feedstock water content). The conversion of VS to gaseous products is controlled by the HRT in an anaerobic digester, however increases in HRT more than 12 days do not considerably increase the destruction of VS. The extent and rate of methane production is affected by the HRT (Gerardi, 2003).

2.16.4. Alkalinity and pH

Anaerobic digestion requires a specific pH to enable the process to proceed steadily as enzymatic activity is facilitated by a specific pH. Acceptable enzymatic activity of acid producing bacteria occurs at pH above 5 while that of methane producing bacteria does not occur at a pH below 6.2 (Gerardi, 2003). Most methane producing bacteria thrive within a pH range between 6.5 and 7.5.

The pH within an anaerobic digester decreases initially as waste is degraded to volatile acids. Alkalinity is achieved as methane producing bacteria begin to consume the volatile acids produced which increases the digester pH and hence it is stabilised. At HRTs of greater than 5 days, methane producing bacteria begin rapid consumption of the volatile acids (Gerardi, 2003).

Within a properly performing digester, a pH of about 6.8 to 7.2 occurs as volatile acids are converted to methane and carbon dioxide (Latif et al., 2017). The carbon dioxide content in an anaerobic digester significantly affects its pH (Gerardi, 2003).

A high alkalinity enhances the stability of an anaerobic digester (Gerardi, 2003). A decrease in alkalinity below the operation level can be used as a sign of impending failure. Causes of a decrease in alkalinity include; 1) accumulation of volatile acids due to failure of methanogenic bacteria to convert them to methane, 2) a slug influent of volatile acids to the digester 3) presence of waste that inhibit methane-producing bacteria activity (Gerardi, 2003).

The chemical characteristics and composition of different types of feedstock directly influences the alkalinity of an anaerobic digester. Predominantly proteinaceous waste is associated with high alkalinity (Gerardi, 2003). The alkalinity produced is due to the production of amino groups (-NH_2) and ammonia(NH_3) as the proteinaceous waste is degraded.

Alkalinity inside an anaerobic digester is essentially in the form of bicarbonates which exist in equilibrium with the carbon dioxide within the biogas produced (Jayaraj et al., 2014) Carbon dioxide is produced as a result of the degradation of organic compounds. The released carbon dioxide leads to production of bicarbonate, carbonic acid and carbonate alkalinity (Equation 2-6) The production of ammonium ions, on the other hand, is as a result of the release of ammonia (Equation 2-7)

Equation 2-6: Production of bicarbonate, carbonic acid and carbonate alkalinity from release of carbon dioxide

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3 \leftrightarrow H^+ + CO_2^{2-}$$

Equation 2-7: Production of ammonium ions from release of ammonia

$$NH_3 + H^+ \leftrightarrow NH4^+$$

The equilibrium that exists as a result of the bicarbonate and carbonic acid alkalinity, carbonate alkalinity as well as ammonia and ammonium ions is a function of digester pH

(Figure 2-10). The principle source of carbon for methanogenic bacteria is derived from bicarbonate alkalinity (Gerardi, 2003).

The feedstock characteristics significantly affect the pH in a digester by production of either organic acids or ammonium ions. During protein degradation, amino groups are yielded and alkalinity is maintained through production of ammonia which dissolves in water in the presence of carbon dioxide to produce ammonium bicarbonate (Equation 2-8)

Equation 2-8: Formation of ammonium bicarbonate by dissolution of ammonia and carbon dioxide in water

$$NH_3 + H_2O + CO_2 \leftrightarrow NH_4HCO_3$$

On the other hand, the degradation of organic compounds yields organic acids that extinguish alkalinity (Jayaraj et al., 2014). For example, the breakdown of glucose yields acetate (Equation 2-9) which neutralises, for example, bicarbonate alkalinity (Equation 2-10) which will only be rectified when methane fermentation occurs (Equation 2-11) as shown in Figure 2-13.

Equation 2-9: Acetate formation by degradation of glucose

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH$$

Equation 2-10: Destruction of ammonium bicarbonate alkalinity

$$3CH_3COOH + 3NH_4\,HCO_3 \rightarrow 3CH_4COONH_4 + 3H_2O + 3CO_2$$

Equation 2-11: Ammonium bicarbonate formation during methane production

$$3CH_3COONH_4 + + 3H_2O \rightarrow 3CH_4 + 3NH_4\,HCO_3$$

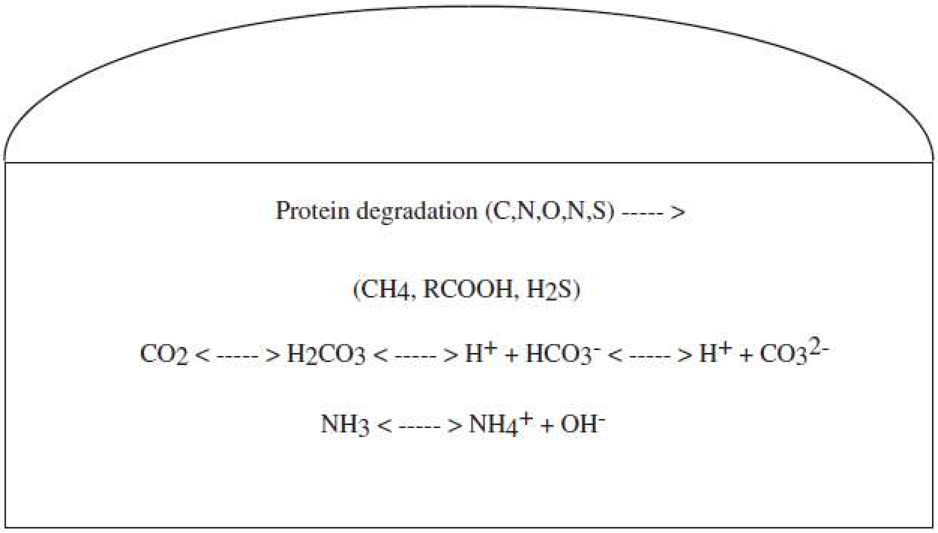

Figure 2-13: pH Equilibrium inside digester

As indicated earlier, a pH range of 6.5 to 7.5 is acceptable for anaerobic digester efficiency though the best occurs in the range of between 6.8 and 7.2 according to Gerardi (2003). pH values above 8 and below 6 are toxic to methane producing bacteria according to Jayaraj et al. (2014) Table 2-9 shows the optimal growth pH for some methanogenic microorganisms.

Table 2-9:Optimum growth pH for some methanogens (Gerardi, 2003)

Genus	Optimal pH
Methanosphaera	6.8
Methanothermus	6.5
Methanogenium	7.0
Methanolacinia	6.6–7.2
Methanomicrobium	6.1–6.9
Methanospirillium	7.0–7.5
Methanococcoides	7.0–7.5
Methanohalobium	6.5–7.5
Methanolobus	6.5–6.8

If the feedstock contains neither alkali compounds nor alkali compound precursors, then Gerardi (2003) suggests alkalinity must be manually added to the digester to maintain stable alkalinity. The quantity of alkalinity to be added in this case should be according to the anticipated acid production of the feedstock.

Alkalinity should be also be added if the acid production rate exceed that of methane production which usually occurs during start-up, overload, temperature variation and inhibition

(Rosato, 2017). Alkalinity can also be "washed-out" of the digester and this usually occurs due to an increased influent flow rate which reduces the required HRT (Gerardi, 2003).

Alkalinity can be induced using several chemicals, some of which are shown in Table 2-10, below. According to Gerardi (2003), Methane producing bacteria require bicarbonate alkalinity and therefore chemicals which directly induce bicarbonate alkalinity are preferred. Among these chemicals, potassium and sodium bicarbonate are very suitable choices based on their relative ease of handling, desirable solubility and minor adverse effects inside the digester. For example overdosing of these chemicals does not quickly elevate pH levels above the optimum and in addition, of all the cations released (Table 2-10), potassium and sodium are the least toxic to (Gerardi, 2003). Methane producing bacteria perform best with bicarbonate alkalinity. Chemicals that produce hydroxide alkalinity like caustic soda are not effective in maintenance of optimal alkalinity in the digester.

Table 2-10:Some chemicals used to correct alkalinity (Gerardi, 2003).

Chemical	Formula	Buffering Cation
Calcium hydroxide (quick lime) Ca(OH)2	Ca^{2+}	Calcium hydroxide (quick lime) $Ca(OH)_2$
Sodium bicarbonate	$NaHCO_3$	Na+
Potassium bicarbonate	$KHCO_3$	K+ Sodium carbonate (soda ash)
Sodium nitrate	$NaNO_3$	Na
Sodium carbonate (soda ash)	Na_2CO_3	Na+
Potassium carbonate	K_2CO_3	K+
Calcium carbonate (lime)	$CaCO_3$	Ca^{2+} Calcium hydroxide (quick lime) $Ca(OH)_2$
Anhydrous ammonia (gas)	NH_3	NH_4^+

Lime can be used to increase a digester pH to about 6.4 but after this, either potassium or sodium carbonate or bicarbonate salts should be used to raise the pH to the optimum level. Lime will increase the pH dramatically but not the alkalinity and hence overdosing with lime could certainly cause the pH to surpass the optimum limit (Gerardi, 2003)

Furthermore, caution must be taken when using quick lime (calcium hydroxide) and soda ash (sodium carbonate) to increase alkalinity in the digester (Gerardi, 2003). These chemicals react first with soluble carbon dioxide in the substrate (Equations 2-12 and 2-13). If this carbon dioxide is used up too rapidly then the carbon dioxide, in the biogas, will replace that in the substrate and thus create a partial vacuum under the digester cover. Ultimately, this could cause the digester cover to collapse.

Equations 2-12 & 2-13: Reaction of sodium and calcium hydroxides with carbon dioxide

$$Ca(OH)_2 + 2CO_2 \rightarrow Ca(HCO_3)_2$$

$$Na_2CO_3 + H_2O + CO_2 \rightarrow 2NaHCO_3$$

Anhydrous ammonia, when used to increase alkalinity, has several benefits and may be used to dissolve scum layers, however it may cause a negative pressure through a reaction with carbon dioxide and, in addition, ammonia may cause toxicity at elevated pH levels (Gerardi, 2003)

Though the pH of a digester can be quickly determined, it is only indicative of what has transpired inside a digester while changes in alkalinity are directly indicative of what is happening inside the digester (McDonald, 2006). pH is the quantity of hydrogen ions in a substrate, while alkalinity is a measure of the quantity of bicarbonate and carbonate. Alkalinity also shows the buffering capacity of a substrate as volatile acids are produced during anaerobic digestion(McDonald, 2006). Finally, according to Rosato (2017) excessive alkalinity should be prevented inside the digester and it can be neutralised by the addition of ferric citrate or chloride.

2.16.5. Carbon to Nitrogen Ratio

Carbon to Nitrogen (C/N); This is a measure of the quantity of carbon relative to oxygen in a substrate. Nitrogen content in a particular feedstock is important in two main ways; it provides an essential nutrient for amino acid, protein and nucleic acid synthesis as well as provides buffering capacity for methanogenic activity inside a digester as volatile acids are produced through conversion to ammonia (Dioha and Ikeme, 2013). However, high nitrogen content in a substrate can lead to excessive ammonia production which leads to ammonia toxicity and conversely, too little nitrogen can lead to nutrient deficiency in the system (Dioha and Ikeme, 2013). Carbon content is generally required for the metabolic activities of anaerobic bacteria and different bacteria use different chemical compounds as a carbon source (Tu et al., 2016) According to Rosato (2017), the ideal C/N ratio is about 30, however, anaerobic digestion can occur at C/N ratios ranging from 10 to 90.

2.16.6. Nutrients and Toxicity.

Anaerobic microorganisms require nutrients to survive and perform the respective roles in the process of anaerobic digestion and at the same time may be hindered by toxic compounds that may be added into a digester (Gerardi, 2003). Sufficient amount of required nutrients may be estimated by ensuring at least a minimum quantity of nutrient as a percentage of the COD load to the digester. Table 2-11 presents the main nutrient requirements of an anaerobic digester.

Table 2-11:Significant Nutrient Requirements for Anaerobic Digesters (Gerardi, 2003).

Nutrient	Micronutrient	Macronutrient	Minimum Recommended (% of COD)
Cobalt	X		0.01
Iron	X		0.2
Nickel	X		0.001
Nitrogen		X	3–4
Phosphorous		X	0.5–1
Sulphur	X		0.2

At the same time, certain constituents of waste may cause toxicity in an anaerobic digester. Toxicity can be caused by any of these types of compounds:

- Alcohols (isopropanol)
- Alkaline cations (Ca2+, Mg2+, K+, and Na+)
- Alternate electron acceptors, nitrate (NO-) and sulphate
- (SO2-)
- Ammonia
- Benzene ring compounds
- Cell bursting agent (lauryl sulphate)
- Chemical inhibitors used as food preservatives Chlorinated hydrocarbons
- Cyanide
- Detergents and disinfectants
- Feedback inhibition
- Food preservatives
- Formaldehyde Heavy metals
- Hydrogen sulphide
- Organic-nitrogen compounds (acrylonitrile) Oxygen
- Pharmaceuticals (monensin) Solvents
- Volatile acids and long-chain fatty acids

Table 2-12 below shows the toxic concentration of common organic and inorganic substances.

Table 2-12: Toxic Values for Common Substances fed into a Digester (Gerardi, 2003).

Inorganic		Organic	
Waste	Concentration (mg/l)	Waste	Concentration (mg/l)
Ammonia	1500	Alcohol, allyl	100
Arsenic	1.6	Alcohol, octyl	200
Boron	2	Acrylonitrile	5
Cadmium	0.02	Benzidine	5
Chromium (Cr6+)	5–50	Chloroform	10–16
Ammonia	1500	Carbon tetrachloride	10–20
Copper	1–10	Methylene chloride	100–500
Cyanide	4	1,1,1-Trichloroethane	1
Iron	5	Trichlorofluoromethane	20
Magnesium	1000	Trichlorotrifluoroethane	5
Sodium	3500		
Sulphide	50		
Zinc	5–20		

2.16.7. Mixing

The content of an anaerobic digester must be mixed for optimal performance. Mixing the contents of an anaerobic digester facilitates even bacteria, substrate and nutrient distribution, and prevents pockets of temperature variation inside the digester. Moreover, close spatial contact between acetate-forming and methane-forming bacteria is essential for their metabolic activities (Gerardi, 2003). Mixing as well enables efficient hydrolysis of substrates, for example, starch from clumping up hence allowing a much larger surface area for hydrolytic bacteria action (Gerardi, 2003). Mixing also prevents hydraulic dead zones which are detrimental to the reaction kinetics involved in the process of anaerobic digestion. Generally, the efficiency of an anaerobic digester is considerably influenced by mixing its content. The benefits of mixing digester content have been summarised in section 2.10.2.1 below. Various researchers (Gomez et al., 2006; Halalsheh et al., 2011; Kaparaju et al., 2008; Ward et al., 2008) argue on the subject of the optimum mixing mode, but majority found that intermittent mixing aids anaerobic digestion. Lindmark et al. (2014) discourages continuous mixing due to its expensive energy needs as well as the possible necessity of a facility that can enhance the separation of the liquid phase from the digested solids. Therefore, Lindmark et al. (2014)

suggests periodic mixing of digester content as an efficient alternative to continuous mixing. In addition, It is important to note that methanogenic bacteria are very sensitive to rapid mixing (Graef and Andrews, 1987).

Additional advantages of mixing digester content include: elimination or reduction of scum build-up as well as thermal stratification or localised pockets of depressed temperature, maintenance of digester sludge chemical and physical uniformity throughout the tank, rapid dispersion of metabolic wastes (products) produced during substrate digestion, rapid dispersion of any toxic materials entering the tank (minimising toxicity) and finally prevention of grit deposition.

2.16.7.1. Methods of Mixing Digester Content

There are many ways to mix the content of an anaerobic digester. They can be categorised into four main systems which include; confined gas injection, unconfined gas injection, mechanical pumping and mechanical stirring systems (Graef and Andrews, 1987). In addition to these methods, some researchers have developed methods for digesters to self-mix their content without any mechanical parts; these have been mainly investigated with respect to domestic digesters[7].

2.16.6.1. (a). Mechanical pumping systems

Mechanical pumping systems are systems that achieve mixing by recirculating the digester content within the digester (Graef and Andrews, 1987). The recirculation can be accomplished by propeller type pumps attached to external or internal draft tubes as well as centrifugal pumps with piping installed on the exterior (Graef and Andrews, 1987). Figure 2-14 presents the different systems and their idealised mixing patterns. (Graef and Andrews, 1987) argues that mechanical pumping systems are most suitable for digesters with fixed covers .

[7] These systems are covered in detail in section 2.10.2.1.4.

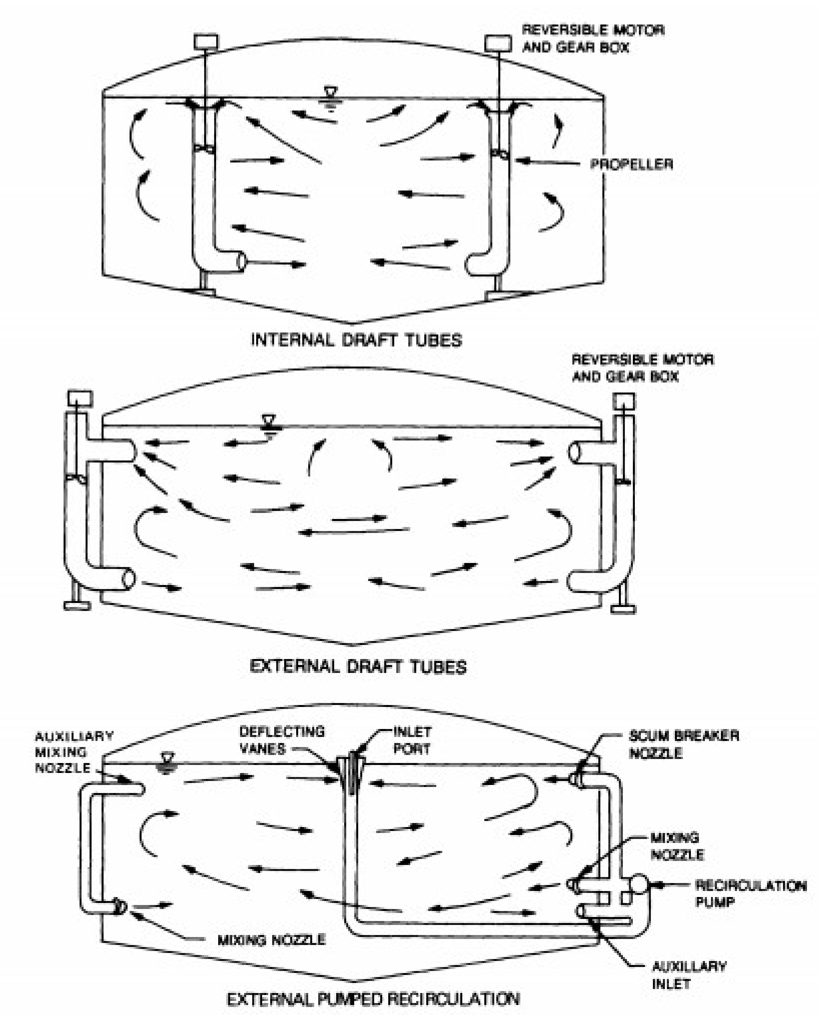

Figure 2-14: Mechanical pumping systems (Graef and Andrews, 1987).

2.16.6.1. (b). Mechanical stirring systems

These systems utilise mechanical rotating impellers to mix the digester content. Two main variations of these systems exist which include low speed turbines and mixers. The idealised patterns of the two systems are shown in Figure 2-15.

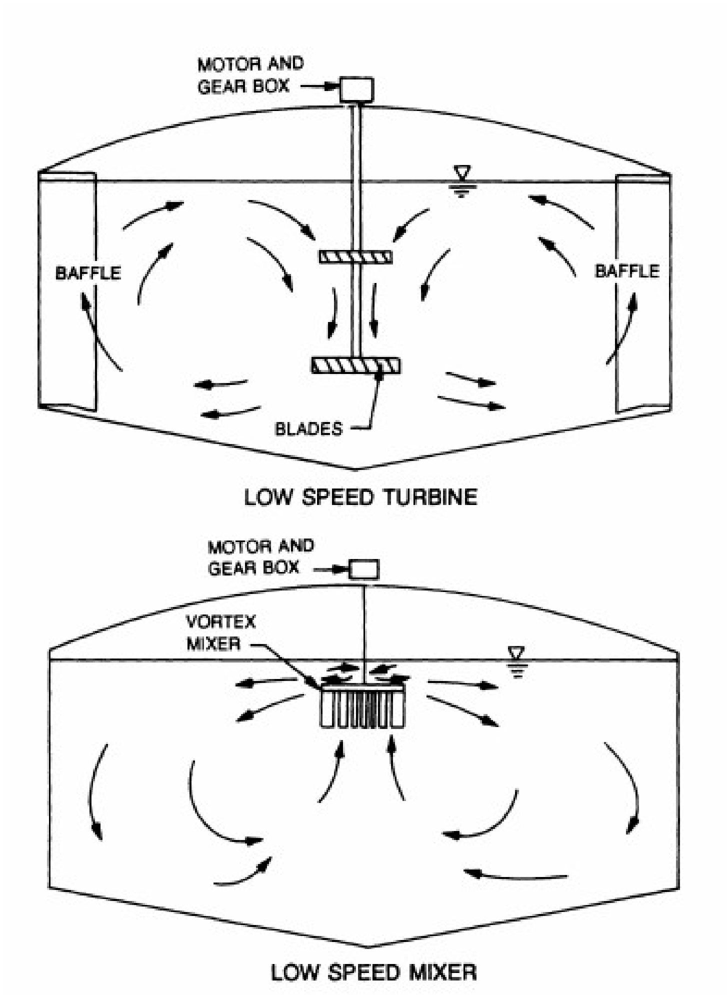

Figure 2-15: Mechanical stirring systems (Graef and Andrews, 1987).

2.16.6.1. (c). Gas injection mixing systems

- **Confined gas injection systems**

These systems operate by collecting gas from the digester and recirculating it through the digester by use of confined pipes (Graef and Andrews, 1987). Figure 2-16 shows the two main systems and their idealised mixing patterns

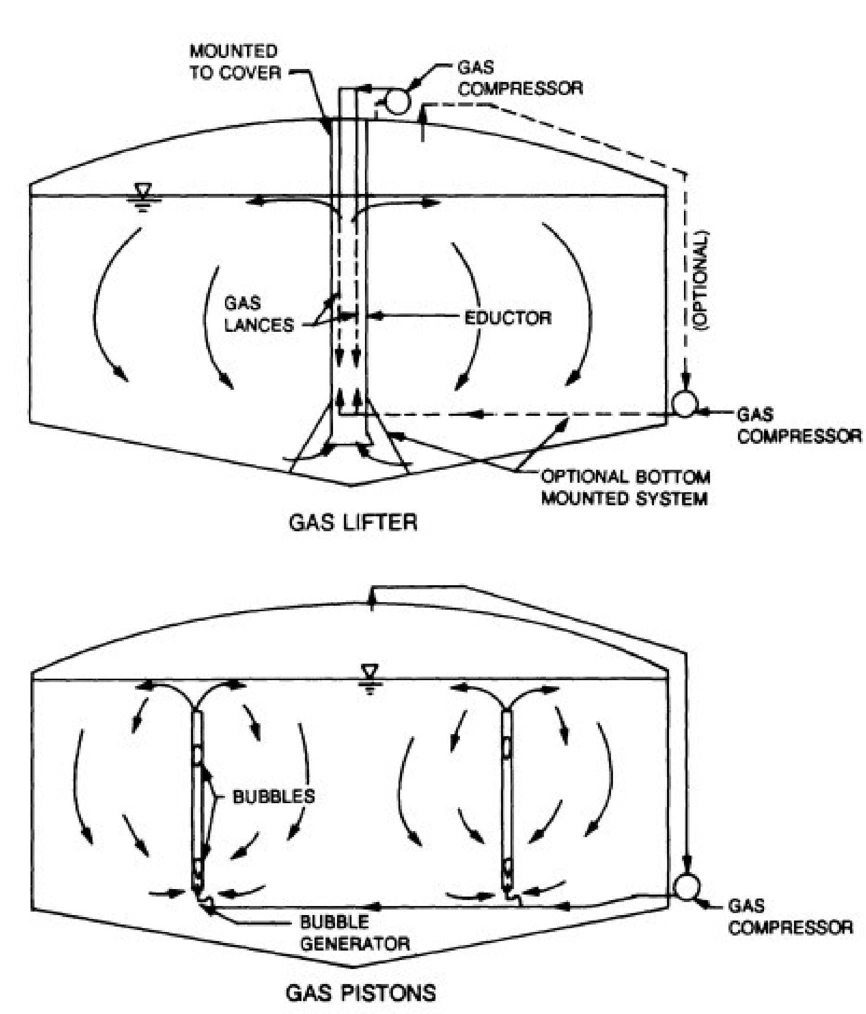

Figure 2-16:Confined gas injection systems (Graef and Andrews, 1987).

- **Unconfined gas injection systems**

These systems work by collecting gas at the top of digester, compressing it and then discharging it through the digester content (Graef and Andrews, 1987). Two main systems are their idealised mixing patterns are shown in Figure 2-17. These systems can be utilised in digesters with floating, fixed or gas holder covers

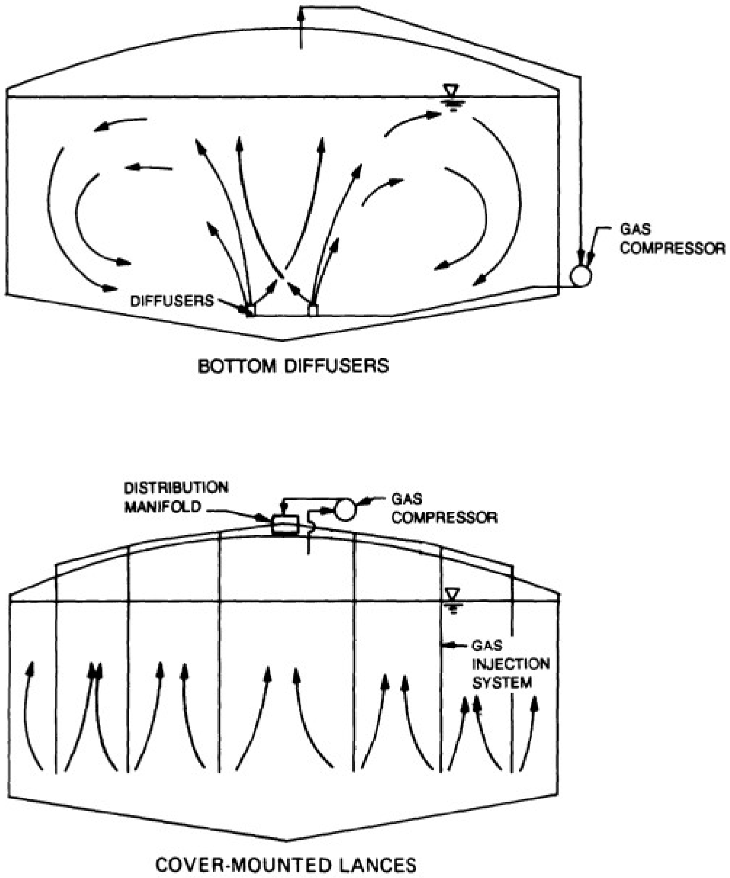

Figure 2-17:Unconfined gas injection systems (Graef and Andrews, 1987).

2.16.1. (d). Self-agitation mixing

The CFDD has a gas pressure forms as a result of the biogas produced at the top of the reactor. This stored gas pushes some of the slurry into the expansion chamber that is usually left opened. As the gas is utilised, the pressure is released causing the slurry to flow back into the digester tank and hence creating a natural intermittent mixing regime which is dependent on the hydraulic variation (Kaparaju et al., 2008).

Jegede (2018) performed an investigation into the effect of different influent TS (3–15%) concentrations and the relative volumetric biogas yield on mixing in lab-scale fixed dome digester types. The results show that the natural intermittent mixing in fixed dome digesters is not adequate at high (>10%) TS concentrations.

Digester slurry tends to behave as a viscoelastic material a high TS values and therefore a lower water content is associated with a higher the yield stress (Jegede et al., 2019) The higher the yield stress, the higher the required force to cause manure to flow. This property is the reason why increased volumetric biogas yield at high (>10%) influent TS is not enough to facilitate optimal mixing in fixed dome digester types. Therefore, to decrease the digester volume and still operate at higher influent concentration rate (ca. 15% TS), the fixed dome digester type can be modified to improve mixing using self-agitating mechanisms by using the produced gas while maintaining simplicity, low initial capital cost, and low maintenance costs. The fixed dome digester has been manipulated by various authors to facilitate efficient mixing. Various researchers have developed different "self-mixing" mechanisms which have been described briefly below:

- **Self-agitation anaerobic baffled reactor (SA-ABR)**

An investigation was performed by Qi et al. (2013) on a "self-agitation anaerobic baffled reactor (SA-ABR)" (Figure 2-15) with agitation caused solely by the release of stored biogas. The content inside the reactor is mixed without any electrical requirements or mechanical equipment. A computational fluid dynamics (CFD) model was used to investigate the flow patterns and agitation process to provide a solid basis for reactor design and optimisation The reactor is regarded as the combined continuous stirred tank and a small plug flow reactor. Self-agitation[8] is achieved by sudden burst of gas stored in the first chamber into the second chamber as well through the varying levels of liquid in the different chambers. The SA-ABR is shown in Figure 2-18 below.

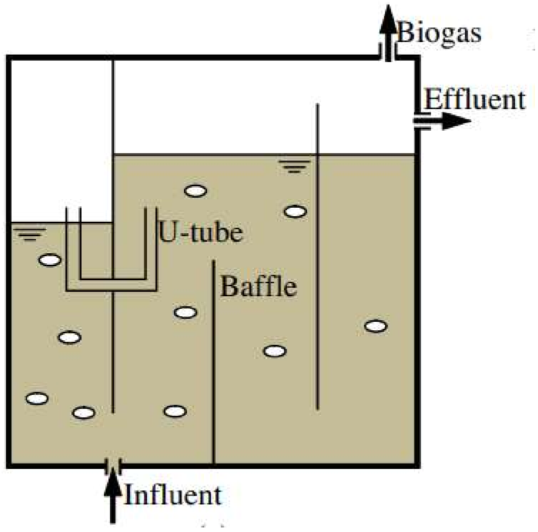

Figure 2-18: Schematics of the SA-ABR. The reactor is composed of four chambers (the 1st, 2nd, 3rd and 4th chamber, from left to right) (Qi et al., 2013).

[8] This phenomenon is well described with respect to the context in a study by Qi W-K, Hojo T and Li Y-Y (2013) Hydraulic characteristics simulation of an innovative self-agitation anaerobic baffled reactor (SA-ABR). *Bioresource Technology* 136: 94-101, ibid..

- **BIMA-Digester System (Biogas-Induced-Mixing-Arrangement)**

GangagniRao et al. (2007) invented and review the BIMA digester that comprises of 3 separate connected sections. The digester, which is shown in Figure 2-19, comprises: i) at least one bottom (11) and at least one upper (12) reaction chamber hydraulically connected through a central draft pipe (13); ii) a feed tank (3) connected to the inlet pipe (4) of the bottom reaction chamber; iii) a feed preparation system (2); iv) an automatic control valve (7); v) a discharge tank (10) to collect the digested slurry (GangagniRao et al., 2007). The three sections are the main, upper chamber and the central tube, to which the feed-pipe is connected. Pre-hydrolysis of the substrate occurs in the central tube. Most of the biogas is produced in the main chamber. Through closure of an automatic valve in the gas pipe between the two chambers, gas produced in the main chamber is collected, which in turn, displaces an equal amount of the digested substrate into the upper chamber, causing a difference in levels and thus a gas pressure in the main chamber. When the required level difference is achieved (mixing pressure), the gas pressure is released by opening the automatic valve in the gas connecting pipe. Thus the substrate displaced into the upper chamber flows back to the main chamber with high velocity. A portion of the slurry flows to the main chamber through the mixing wings while the rest flows back through the mixing shafts. On account of this, fresh substrate, scum and sediments are seamlessly remixed with the contents of the main chamber. Thus the new pre-hydrolysed substrate is mixed with active biomass in the digester. Another portion of the digested substrate, which flows out through the mixing shafts, pours onto the surface of the main chamber, thus avoiding formation of scum (Figure 2-19).

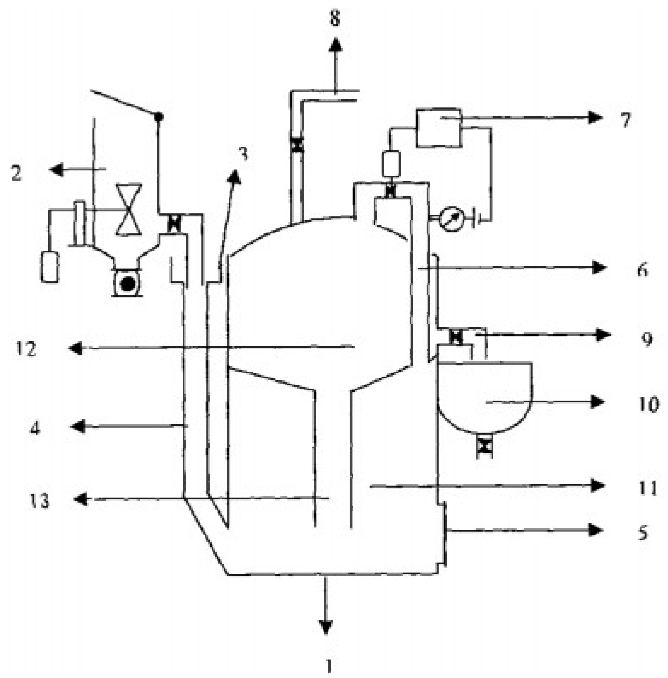

Figure 2-19: BIIMA Digester System (GangagniRao et al., 2007) .

- **“Self-mixed anaerobic digester” (SMAD)**

Anaerobic digestion of poultry litter was studied by Gangagni Rao et al. (2013) in a conventional fixed dome digester and self-mixed anaerobic digester. The performance of the two was compared and it was found that the SMAD performed better in terms of methane yield and stability.

The SMAD (Figure 2-20) has two compartments (upper and bottom chamber). Both the compartments are hydraulically linked by a central draft pipe (Gangagni Rao et al., 2008b). Fresh slurry is fed into the bottom compartment of the digester and pressure developed in the bottom chamber due to biogas production is used for mixing the slurry. Slurry moves up and down in both the digester’s compartments through the draft tube due to the differential pressure that occurs in both compartments. Movement of the slurry across the two chambers is achieved by automatic opening of the valve as per the set pressure. During this movement, the slurry creates vibrant mixing whenever it falls into the bottom chamber and therefore the slurry in the bottom chamber becomes homogeneous and well mixed.

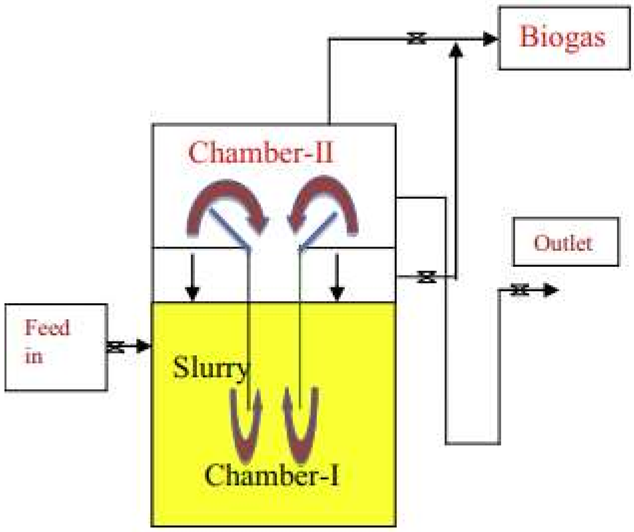

Figure 2-20: Schematics of the SMAD (Gangagni Rao et al., 2008b)

- **"Optimised Chinese Dome Digester"**

Jegede et al. (2019) developed an "Optimised Chinese Dome Digester" with a self-mixing mechanism. Self-agitation was achieved by placing a baffle in the headspace of the digester (Figure 2-18) and placing the gas outlet at compartment B. When biogas is extracted from compartment B, the pressure in the compartment tends to atmospheric pressure while some gas is stored in compartment A with no pressure decrease. The gas stored in compartment A will cause a pressure build-up as more biogas is produced. When enough pressure is built up in compartment A, some of the biogas will escape into compartment B creating a two-minute self-mixing cycle (Jegede et al., 2019). Ciborowski (2001) showed that solids content of cow dung greater than 10% require dilution before anaerobic digestion to enable optimal performance of the digester. According to Jegede et al. (2019), this digester produced 40% more methane than the blank that it was tested against and in addition showed superior digestion treatment efficiency and ability to operate at higher influent TS(15%) concentrations. The optimised CFDD has been shown in Figure 2-21 below.

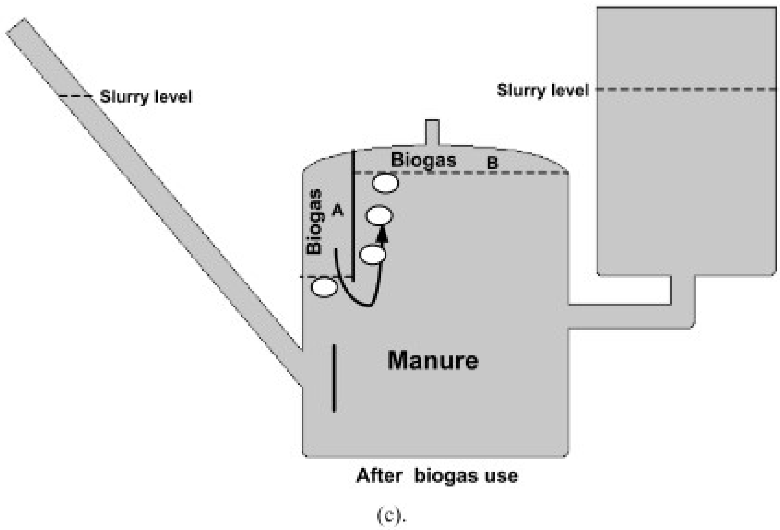

Figure 2-21:Self mixing mechanism after use of biogas

2.16.8. Oxidation-Reduction Potential

The ORP, measured in millivolts(mV), of a substrate is the tendency of a chemical molecule, or group of molecules or radicals to be reduced (lose electrons) (Rosato, 2017). It is easily measurable by a probe. ORP is largely employed as a water quality parameter for environmental protection and treatment of waste water. According to Rosato (2017), values of ORP between 0 and +2000mV indicate aerobic activity while those between 0 and -2000 indicate anaerobic activity. Blanc and Molof (1973) indicate that typical optimum ORP values for methane production range between -220 and -290 mV, however, Gerardi (2003) argues that methane production occurs at values less than -300Mv, and furthermore, suggests the values shown in Table 2-13 for respective types of degradation.

Approximate ORP values, mV	**Molecule Used For Degradation Of Substrate**	**Type of Degradation**
>+50	Oxygen (O_2)	Oxic (aerobic)
+50 to -50	Nitrite (NO-) or nitrate (NO-)	Anoxic (anaerobic)
<-50	Sulphate (SO_2-)	Sulphate reduction (anaerobic)
<-100	Organic (CHO)	Fermentation (mixed acids and alcohol production)
<-300	Organic(CHO), CO_2, CO, H_2	Fermentation(methane production)

Table 2-13: Cellular activity and ORP

2.17. The importance of feedstock

Feedstock is a very broad topic involved with an array of interdependences connected to anaerobic digestion. The quality and quantity feedstock directly influences the reactor design, operational considerations, economic considerations, and the bacterial activity. The process of anaerobic digestion is dependent on the type of feedstock used (Steffen et al., 1998). Anaerobic digestion can only occur on biodegradable organic substrates however different substrates degrade faster than others and this is dependent on the chemical composition of a particular feedstock (Steffen et al., 1998). Historically, sewage sludge and animal dung have been the main substrates for anaerobic digestion (Bernhard et al., 2013). Cow dung has been reported by several authors to be a suitable feedstock for anaerobic digestion due to its ideal C/N ratio and buffering capacity (Ibn Abubakar and Ismail, 2012; Castro et al., 2017; Hasan et al., 2018). Furthermore, anaerobic digestion of cow dung alleviates it detrimental greenhouse effect on the environment caused by its methane emissions (Ibn Abubakar and Ismail, 2012). However, during the 1970s, increased environmental awareness coupled with increased demand for waste management strategies and renewable forms of energy broadened the range of feedstock and hence municipal and industrial waste were introduced(Steffen et al., 1998). In addition, recent concerns regarding over landfilling, has led engineers to consider alternative treatment methods, such as anaerobic digestion, for some waste streams prior to disposal and in turn save landfill space and convert the material into renewable energy (Steffen et al., 1998). Table 2-14, below, shows some sources and types of organic wastes that can be treated using anaerobic digestion.

Table 2-14: Some sources and types of organic wastes that can be treated using anaerobic digestion (Steffen et al., 1998).

AGRICULTURE	INDUSTRY	COMMUNITIES
• Dung (Cattle, Pig, Poultry) • Energy Crops • Algal Biomass • Harvest Remains	• Food/Beverage Processing • Dairy • Starch Industry • Sugar Industry • Pharmaceutical Industry • Cosmetic Industry	• OFMSW • MSW • Sewage Sludge • Grass Clippings/Garden Waste • Food Remains

	• Biochemical Industry • Pulp and Paper • Slaughterhouse/Rendering Plant	

More complex polymetric waste require longer periods of degradation. Lignin anaerobic degradation is hardly perceptible because lignin is difficult for anaerobic bacteria to degrade. Substrates containing cellulose are also associated with long degradation periods because of the same reason although cellulose is more readily biodegradable than lignin. Hemicellulose, carbohydrates and protein can be degraded within a few days however the rate of degradability is dependent on the bio-chemical factors as well as the conditions to which a substrate is exposed (Bernhard et al., 2013). According to Rosato (2017), these conditions include: pH, BMP, OLR, alkalinity, VFA concentration profile, concentration of dissolved H2, and quantity and quality (composition) of biogas.

2.18. Digestate

Digestate is a by-product of the process of anaerobic digestion. It is rich in nutrients such as potassium, nitrogen and phosphorus which make it ideal for use as a fertiliser (Makádi et al., 2012). The composition and quality of digestate is dependent on the material fed into the digester and the specific operational conditions of the digester (Logan and Visvanathan, 2019).

If the digestate is not considered waste, it is important for it to meet standards for its disposal to prevent it from polluting the environment (Logan and Visvanathan, 2019). These standards provide limits on the concentration of particular constituents of the digestate that may be of concern, if too high. These mainly include; the COD, pathogens and heavy metals (Logan and Visvanathan, 2019). It is important to note, however, that there are no official regulations that specifically govern the disposal of digestate in South Africa (Mackay, 2015). However, according to Mackay (2015), the reuse of liquid or solids from digestate must comply with the target quality for each criteria stipulated, for waste water and sludge, by the Department of Water and Sanitation.

2.19. Biogas technology as a sanitation solution in rural areas

According to Tayler (2018) ,sometimes engineers assume that sewerage which is conveyed to a wastewater treatment plant is the only viable sanitation method, but in reality fully sewered plants are in very few developing countries, and the status quo is likely to persist for a foreseeable future. This therefore necessitates the use of on-site sanitation systems (Tayler, 2018). A complete sanitation system comprises of a chain of technologies, each fulfilling a specific function such as the toilet, transportation, storage, treatment and the reuse or sanitary disposal of effluents, according to Mang and Li (2010). According to Tayler (2018), a sanitation service chain comprises of: the capture of faecal sludge or septage, storage, removal and transport for treatment or disposal on or offsite. Faecal sludge refers to material containing faecal solids and urine that accumulates in a pit, vault or tank, while septage refers to solids and liquids that accumulate in a tank, pit or vault in a sanitation system that uses water (Tayler, 2018).

Anaerobic digesters have been used for treatment of faecal sludge and septage in several countries for both onsite and offsite disposal (Tayler, 2018). Large scale digesters are mostly used at large waste water treatment works as part of the treatment process. These large scale digesters however require large tanks, mixing and heating. Hence because of their complexity, they are not suitable for faecal sludge and septage treatment in rural areas (Tayler, 2018).

According to Cheng et al. (2017) small –scale anaerobic digesters have been used for both faecal sludge and septage in rural areas. One example of the use of an anaerobic digestion process system solely for sanitation ,in South Africa, is the three crowns school project whereby wastewater is treated for re-use (Wells, 2011). Since anaerobic digesters do not require power, they can be utilised in areas with no reliable energy source and operation capacity. The advantages of anaerobic digesters, in the context of faecal sludge and septage treatment, include; production of energy, reduction of chemical and biochemical oxygen demand, and pathogens. In turn, they contribute to protection of natural resources such as soil and water (Modjinou and Darkwah, 2015). Because faecal sludge and septage in rural areas is associated with high oxygen demand, decentralised systems that use anaerobic digesters usually require a proceeding treatment process to make the effluent suitable for sanitary disposal, and especially, to make effluent suitable for re-use (Tayler, 2018). However, this necessity is usually dependant on the expected flow rate relative to the digester’s size. The aforementioned factors will affect the digester’s Hydraulic Retention Time (HRT), and hence an interrupted HRT results in incomplete removal of pollutants (COD and pathogens). Table 2-15 below shows some limited available data on the treatment performance of bio-digesters; it shows that a shorter HRT results in a lower treatment efficiency, however, various other factors such as temperature and the digester type will affect the treatment efficiency. According to Tayler (2018), the few available studies suggest that anaerobic digesters can reduce up to 40% of the COD. However, Than et al. (2014) has reported removal efficiencies of up to 86% during laboratory batch tests.

Table 2-15: Some reported treatment performance of bio-digesters (Tayler, 2018)

Location and source of information	System type and volume	Influent source	Influent characteristics	HRT (Days)	Treatment efficiency and biogas production
Kanyama, Lusaka, Zambia (BORDA, personal communication, 2017)	Fixed-dome digester (brick): 58 m^3 volume; (53m^3 liquid volume)	Faecal sludge from dry, unlined household pit latrines	1.2 m^3 of faecal sludge per day, dry solids 12–20% and COD typically 80,000 mg/l1 (plus 1–2 m^3)	20	20–25% COD removal1 63 l biogas/ kg dry solids
Devanahalli, Bangalore, India (CDD, personal Communication 2017)	Fixed-dome digester (pre-fabricated fibreglass) 6m^3 volume in parallel (4.4 m^3 liquid volume each)	Septage from household leach pits (wet) and septic tanks (Note: figures are for solid stream after solids–liquid separation)	1.1 m3 inflow per day Dry solids = 4–6% COD = 20,000–60,000 mg/l	8	<5% COD removal1 19 l biogas/ kg dry solids
Kumasi, Ghana (Sarpong, 2016)	Geobag digester 8 m^3 volume in series	Fresh faecal material from containerised toilets (emptied 2-3 times a week)	0.4 m3/day (for 21 days per month) COD = 35,000 mg/l (range: 20,000-40,000 mg/l) Dry Solids = 5-10%	90	39% COD removal No biogas information

(continued)

Mang and Li (2010) provides an overview of some biogas sanitation systems which includes; anaerobic baffled reactors, septic tanks, anaerobic filters and up flow anaerobic sludge blankets (UASB), though the latter is suited to large industrial effluents. According to Mang and Li (2010), a septic tank is synonymous to a biogas septic tank in which the anaerobic conditions are referred to as “septic” hence its name. However, a typical septic tank system consists of a water tight tank that is proceeded by a soak-away drain without any re-use of effluent and without any biogas capture. Different combinations of sanitation units can be combined with each other to benefit from the specific advantages of different systems (Mang and Li, 2010). For example, Bremen Overseas Research and Development Association (BORDA) implements anaerobic digesters, as part of their Decentralised Wastewater Treatment Systems (DEWATS); which are commonly proceeded by an anaerobic baffled reactor and finally constructed wetlands or ponds (Mang and Li, 2010).

2.20. Pathogens and Anaerobic Digestion

As the World health Organization advocates for worldwide sanitation, the disposal of sewage requires strict monitoring (Zhao and Liu, 2019). This is because the direct discharge to land of sewage as well as large quantities organic of poses a serious health risks due to their associated high pathogenic content (Lemunier et al., 2005; Zhao and Liu, 2019). According to Lemunier et al. (2005), anaerobic digestion can largely and efficiently deactivate some viral, parasitic and bacterial pathogens, however deactivation is lower in mesophilic than thermophilic temperature. Harrison and Saunders (2019) reported a 90% to 95% reduction in pathogenic bacteria at mesophilic temperatures and similarly, Harrison et al. (2011) established a 2.5log reduction in *E Coli* within dung anaerobic digestate. In addition, Cote et al. (2006) reported a 99.67% to 100% reduction in indigenous *E Coli* and also achieved undetectable levels of indigenous *Salmonella* strains and protozoa. According to Harrison and Saunders (2019), anaerobic digestion can reduce the following pathogens: *Salmonella, Generic Escherichia coli, Escherichia coli O157:H7, Mycobacterium paratuberculosis (Johne's disease), Bovine enterovirus (BEV), Enterovirus, Faecal Coliform and Cryptosporidium.* Anaerobic digestion has shown to have no effect on Bovine Spongiform Encephalopathy (BSE) which is an infectious agent (Harrison and Saunders, 2019). However, according to Mang and Li (2010), some pathogens are not deactivated within fully mixed mesophilic conditions. Therefore, Mang and Li (2010) suggests that recommendation on the use of digestate should exclude spray irrigation to vegetable and limit irrigation to fruit trees. Otherwise, digestate can be post-treated to suit respective disposal limits, or can be disposed of using a soakaway to protect people from exposure to pathogens (Tayler, 2018).

2.20.1. Pathogen Indicators

An indicator organism is one whose presence shows the extent and nature of contamination in a substrate. An ideal pathogen indicator should; (i)be specific to the substrate, (ii)always be present and absent at the same time with pathogens, (iii)lend itself to routine tests without confusion of results due to extraneous organisms and (iv) not be a pathogen itself for laboratory personnel safety (Peavy et al., 1985).

A pathogen indicator test is one that is performed to determine the presence and extent of pathogen contamination. Analysing a sample for all known pathogens can be a tedious process therefore these tests are performed when there is suspicion of the presence of those particular microorganisms. At other times, an indicator organism test is performed (Peavy et al., 1985).

Different substrates require different indicator organisms to assess their degree of pathogen pollution. The indicator organisms commonly used for food waste, cow dung and human excreta include: *Escherichia Coli (E Coli), Faecal Streptococci* and *Faecal Coliforms*

Enterococci have lately emerged as nosocomial pathogens. Their ubiquitous nature governs their reoccurrence in foods as pollutants. Additionally, the notable resistance of *Enterococci* to unfavourable environments explains their ability to colonise different ecological niches as well as how they spread within the food chain through contaminated foods and animals. *E.Coli* functions as a reliable indicator of faecal contamination as well as the possibility of the presence of enteropathogenic and/or toxigenic microorganisms within food, water, cow dung and faecal sludge (Manyi-Loh et al., 2016). *Faecal streptococci,* has been advocated as an indicator of faecal contamination. However, various practitioners have found them to be of limited value as sole indicator but useful in conjunction with either the coliforms or faecal coliforms in establishing the source of contamination.

3. METHODOLOGY

3.1. Introduction

The study was based on an area within Ndwedwe Local Municipality (NLM), KwaZulu Natal. The study has been contextualised within two interrelated but district rural bioenergy projects located in Ndwedwe Local Municipality, facilitated by the South African National Energy Development Institute (SANEDI) and the National Lotteries Commission (NLC). The interventions related to these projects in NLM have been described and in addition, experiments have also been described with the aim of investigating the characteristics of the possible feedstock as well as their biomethane potential (BMP). Finally, an experiment to investigate a technically optimised anaerobic digester was performed. The methods described in this chapter have been used to derive an optimised anaerobic digestion process system in terms of the design, infrastructure and overall performance. During the studies, both quantitative and qualitative approaches were used with qualitative approaches typically using empirical, oral or written methods, for example interviews, while quantitative methods were used to attain numerical data.

3.2. Case Study

3.2.1. Ndwedwe Local Municipality (NLM) Description

NLM is an administrative area situated within the ILembe district of Kwazulu-Natal, South Africa. The area, covered by NLM, is approximately 1093 km^2 with coordinates at 29°30’0’’South and 30°56’0’’East. It is found approximately 20km inland, and parallel to the Kwazulu Natal coastline. NLM covers up to a third of the ILembe district, and thus is the largest of the four municipalities within the district, which include, the Maphumulo, Mandeni and KwaDukuza local municipalities as shown in Figure 3-1 below.

NLM has a population of about 140,000 people, who are predominantly black, with less than 4% in possession of a higher education qualification, and less than 30% with a high school qualification. 70% of the population has access to electricity for lighting, while about 4% of the households have a flush toilet connected to a sewer system (Main, 2019). According the Ndwedwe Integrated Development Plan (2018), it is estimated that 66% of the households in the area still lack access to potable water, as a result of poor maintenance or depletion of the water source. The area is significantly underdeveloped and poor with families commonly dependant on subsistence farming.

External access and internal linkage to and in the area is limited to “East-West” roads while “North-South” links are limited and of a poor quality. Majority of NLM’s detailed future planning is dependent on strategies that are yet to be developed for the ILembe district. However, the major short-term goals that have been established for NLM are greatly focused on the provision of basic services and infrastructure to the population which is severely deficient at present (Main, 2019).

Figure 3-1: Showing the location of NLM within ILembe District (Google Maps,2018)

3.2.2. SANEDI Working for Energy Programme and Rural Household Biogas Project

The SANEDI Working for Energy programme is a social programme that was initiated in 2008/2009 with the aim of providing energy services, obtained from renewable sources, to rural and low income households. These interventions are designed with a specific aim of promoting job creation, skills and community based enterprise development. This programme led to the development of the NLM rural household biogas project which is described below.

3.2.2.1. Rural Household Biogas Project Description

During September of 2014, Khanyisa Projects accomplished an award winning rural biogas project in the NLM area, in KwaZulu Natal under the, SANEDI, Working for Energy programme (SANEA Energy Awards 2014). The project involved the installation of 26 anaerobic digesters at selected households in the NLM, that makes up part of the Ilembe District Municipality. The project strategy also involved the teaching and mentoring of some local builders to improve labour quality as reserve manpower for any future extension to the project. In addition, the project also involved the installation of rain water harvesting and solar lighting systems at each of the households as part of a comprehensive sustainable energy intervention (Working for Energy programme). The main objectives of the project were: reduction in greenhouse gas emissions, improvement to quality of life, skills development and increase in biogas awareness.

3.2.2.2. Site Selection.

A list of criteria for selection of beneficiaries was developed which included: possession of a minimum of two cows or other livestock which are kept at a location near the household, agricultural activities, reliable water source, material availability, positive attitude to the scheme and signage of a commitment form.

Stakeholder engagement took place throughout the project, but was intensive during the planning phase. Key stakeholder activities included: various telephonic discussions with Ilembe District officials, stakeholder meetings with NLM stakeholders (the Mayor and the local economic development committee), the Department of Agriculture, Ward Councillors and their development workers as well as traditional authorities.

Site visits to Ward 14 and 16 took place in May 2013 to assess the topography, access to water and livestock activities. It was observed that Ward 16 was extremely remote with many houses having limited access to water. Water is an essential part of the construction phase and operation of the anaerobic digester. The local economic development committee selected Wards 14 and 16 for the programme, however, due to the lack of co-operation from the Ward 16 Councillor and after consultation with key officials, it was decided to replace Ward 16 with Ward 18. This ward was slightly less remote and the Councillor was more co-operative. The project was finally rolled out resulting in a breakdown of beneficiaries per ward, with 16 and 10 digesters to be built at ward 14 and 18, respectively. The exact positions and co-ordinates of the digesters are shown in Table 3-1 overleaf.

Table 3-1:Household beneficiaries and locations of households in NLM

No	Household Name	Area	Ward	Latitude	Longitude
1.	Nxumalo	Wosiyane	18	29°31'59.46"S	30°48'23.95"E
2.	Mgidi	Wosiyane	18	29°32'22.19"S	30°48'27.06"E
3.	Jali	Wosiyane	18	29°32'25.84"S	30°49'59.68"E
4.	Hlambisa	Shangase	18	29°32'20.98"S	30°51'35.98"E
5.	Memela	Shangase	18	29°33'11.18"S	30°53'18.02"E
6.	Shangase	Shangase	18	29°32'45.60"S	30°52'46.60"E
7.	Gama	Shangase	18	29°32'43.51"S	30°53'27.44"E
8.	Cibane	Mission	18	29°33'31.27"S	30°55'54.36"E
9.	Ngcobo	Mission	18	29°34'36.97"S	30°55'50.39"E
10.	Ngcobo	Mission	18	29°34'42.06"S	30°56'5.09"E
11.	M. Ngcobo	Bhentamu	14	29°33'45.18"S	31° 0'45.88"E
12.	M. Ndlovu	Bhentamu	14	29°33'39.28"S	31° 0'50.03"E
13.	B. Zuma	Bhentamu	14	29°34'29.63"S	31° 0'34.58"E
14.	N. Ngcobo	Ntaphuka	14	29°33'38.93"S	30°59'46.58"E
15.	Phakathi	Ntaphuka	14	29°33'47.81"S	31° 0'0.79"E
16.	Shandu	Ntaphuka	14	29°33'31.67"S	30°58'15.45"E
17.	Mlangeni	Ntaphuka	14	29°33'10.41"S	30°58'49.07"E
18.	Magwaza	Ntaphuka	14	29°33'16.31"S	30°59'30.76"E
19.	Ngiba	Qadi	14	29°33'57.62"S	30°59'15.75"E
20.	Mngadi	Qadi	14	29°33'55.96"S	30°59'15.05"E
21.	J. Ngcobo	Qadi	14	29°34'25.05"S	30°59'27.01"E
22.	Hlongwa	Ogunjini	14	29°34'43.15"S	30°58'40.51"E
23.	Mthembu	Qadi	14	29°34'20.53"S	30°59'58.33"E
24.	P. Ngcobo	Qadi	14	29°33'53.96"S	30°58'45.58"E
25.	Mbambo	Ogunjini	14	29°35'17.32"S	30°58'39.58"E
26.	Mdima	Ogunjini	14	29°34'50.70"S	30°58'29.33"E

The finished project led to the development of a refurbishment research and development project, also through SANEDI, which sought to evaluate the status of these interventions and find solutions to identified technical gaps in the model of biogas provision[9].

3.2.3. The National Lotteries Commission (NLC).

The National Lotteries Commission (NLC) is the only National Lottery licence holder and regulator in South Africa. The NLC regulates several lotteries that include: society lotteries, sports pools, competitions and raffles. The NLC also regulates and monitors the organisation of various lottery competitions, including those organised by non-profit organisations and companies to raise funds and promote goods and services, respectively.

[9] Full details of this project can be found in section 3.3.

The NLC also functions as a grant funder to projects that improve the livelihood of everyday South Africans. The grant funds are focused, mainly, on areas that require sufficient support to bring about change and growth within impoverished communities. The impact of the grant funds is designed to play a pertinent role in changing the lives of people (National Lotteries Commission, 2019).

3.2.3.1. NLC- UKZN Rural Bio-Energy Project

The main objective of this interdisciplinary applied research and demonstration project, was to develop a contextualised off-grid and integrated green solution to combat energy poverty. as well as, improve the quality of life in deep rural communities in KZN. An integrated off-grid energy model for sustainable communities will be designed and piloted in 20 deep rural households in KZN, including: 1) small scale bio digesters to treat farm and food waste, 2) energy efficient measures including solar lighting, solar water heater geysers and thermal insulation, 3) rain water harvesting, and 4) household sanitation systems including the treatment and disposal of digestate from the mini-bio digesters. The project aims were as follows: to design a model to improve the sustainability of deep rural households that can be replicated throughout South Africa; to manage infrastructure sustainability transitions in deep rural communities, to develop off-grid and integrated green retrofit solutions (i.e. energy, water and sanitation) for deep rural households and finally to assess the potential for sustainable infrastructure projects to further regional green economy objectives (i.e. create green jobs).

The original proposal for this project proposed interventions to occur in the area south of the community owned Somkhanda Game Reserve in north eastern KwaZulu-Natal. In this original proposal The African Conservation Trust (ACT) would serve as managing non-profit organisations, facilitating project activities, as they are currently having a strong presence within those communities. However, administrative challenges between ACT and the University of KwaZulu-Natal prevented any forward movement with any partnership with ACT, necessitating a change in project location to ILembe District. This led to the development of a new project titled as “The Rural Bio-Energy Project” funded by the NLC.

It was evident from the aforementioned household project as well as from literature, that biogas becomes more sustainable if it is connected to more users. Therefore, a decision was made to design anaerobic digestion process systems for 5 selected ECDCs in the same area. The system was designed as an optimised anaerobic digestion process system. The phases of design for the project have been described in detail.

3.3. Project Definition

It is important to note that the research conducted formed part of two projects which have been briefly mentioned above. In order to conduct the research, data was utilised with respect to both projects. The two projects have been assigned letters "A" and "B" in parentheses and can be clearly defined as follows:

(A) NLM Rural Household Biogas Project Site Investigation and Troubleshooting ("SANEDI Refurbishment Project").

This project was funded by SANEDI and was titled as the "SANEDI Refurbishment Project". The project is a follow-through from the original project that was started in 2014. The main aims of the project were to critically investigate each of the twenty-six household biogas systems, provide maintenance (immediate solutions to identified issues in the system), and provide long term solutions to all identified issues in the system. The results will ultimately be used to optimise anaerobic digestion process systems in rural areas of South Africa.

(B) Anaerobic Digestion Process System Implementation at Five ECDCs in NLM ("The Rural Bio-Energy Project").

This project was funded by the "National Lotteries Commission, South Africa" and was titled "The Rural Bio-Energy Project". The main aim of the project was to contribute to biogas provision in rural areas in South Africa. As mentioned earlier, biogas becomes more sustainable at a higher economy of scale, therefore the project was implemented at five ECDCs. "The Rural Bio-Energy Project" used the results from the "SANEDI Refurbishment project" to provide biogas optimally in terms of technology, process and infrastructure.

This project involved the implementation of biogas digesters, ablution blocks and rainwater harvesting tanks at five ECDCs in NLM. The scope of work included: engineering design, community engagement, construction management including sourcing and contracting local contractors and local labour, procurement of materials, engineering quality control and financial management of the budget.

3.4. Data Collection

The data that enabled the study was obtained using both quantitative and qualitative methods, with qualitative methods typically using an empirical approach, while quantitative methods were used to obtain numerical data. The data collection was facilitated by the two aforementioned projects and therefore the data collection methods are interlinked with the projects. The methods that were used to collect data include: participatory observation, engineering site investigation and troubleshooting, engineering design (desktop study, site and technology selection as well as overall system design), laboratory waste characterisation tests, biogas yield tests and finally prototyping. The methods have been elaborated further within the sections that follow.

3.5. Interviews (Participatory Observation)

Interviews were conducted to provide an indication of the socio-economic aspects of the household biogas interventions, as well as facilitate the activities related to the anaerobic digestion process systems at the five ECDCs, such as the site selection process.

The interviews comprised of open ended questions that were standardised. The original interviews and responses with respect to the household interventions can be found in Appendix A. The results of the interviews that were conducted during the ECDC site selection process have been shown in section 4.5.1. Unstructured interviews (participatory observation) were also performed to determine the time spent cooking at each ECDC as well as their principal energy source and its cost.

3.6. (A) NLM Rural Household Biogas Project Site Investigation and Troubleshooting

The purpose of this investigation was to critically examine the performance of the aforementioned model of biogas provision currently being implemented in South Africa by SANEDI through an investigation of 26 SANEDI household digesters located in NLM, KwaZulu-Natal. The 26 households were mapped out, as shown in Figure 3-2 below, and visited to carryout investigations.

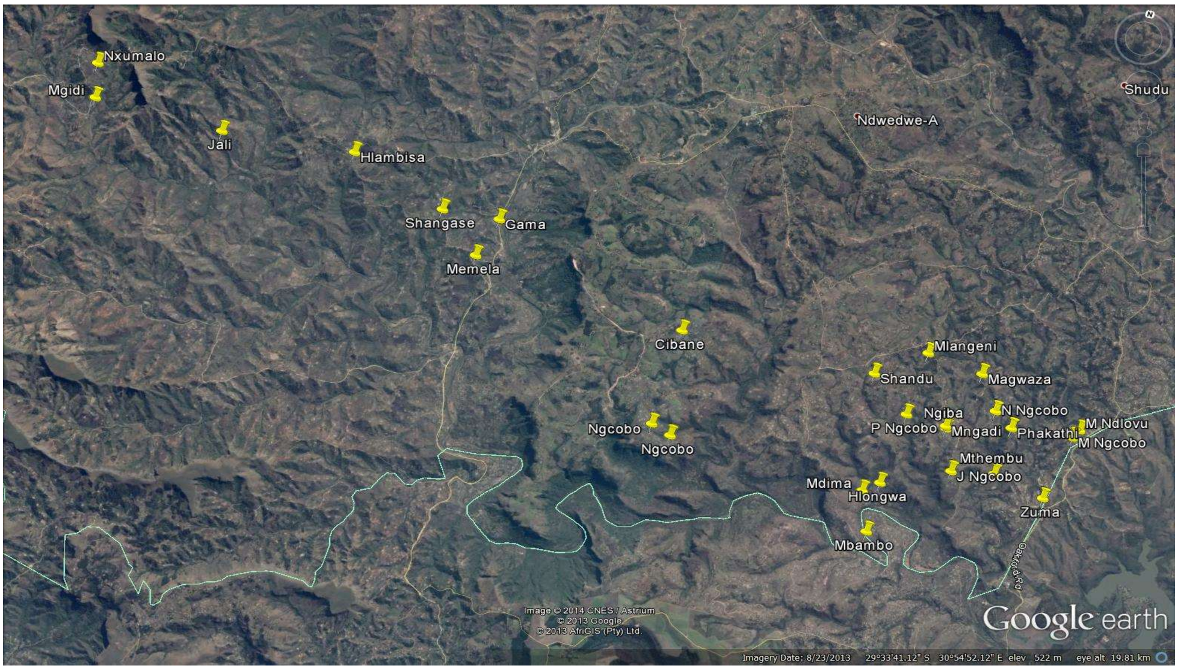

Figure 3-2: Map showing positions of each of the household biogas beneficiaries.

Utilising a mixed-methods approach, the study draws on a variety of data sources, including: a technical engineering investigation of the 26 biogas systems on performance and common maintenance issues; qualitative interviews conducted in selected households, and; experimental quantitative methods, including characterisation tests and a bio-methane potential (BMP) test, in order to assess the suitability of various locally available feedstock for biogas production and to assess the quality of digestate currently being produced. A general schematic of the household biogas systems has been shown in Figure 3-3.

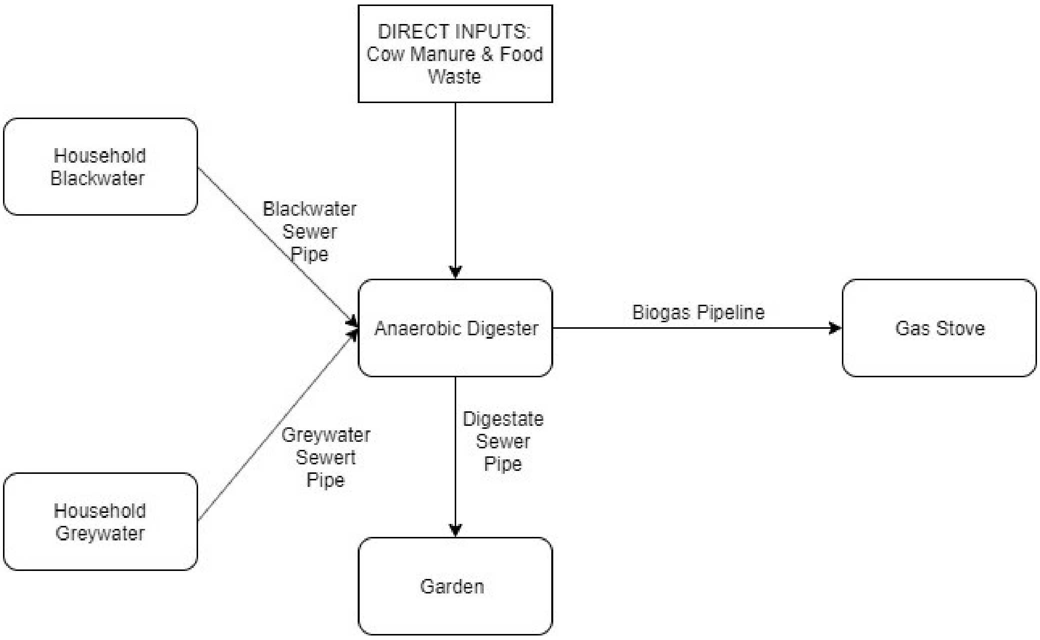

Figure 3-3: Schematic of the SANEDI Rural Household Biogas Systems

The aim of visiting and investigating the sites was to identify pitfalls in the system in order to rectify the identified issues and using them to provide recommendations to optimise anaerobic digestion process systems. The problems on site were investigated with respect to the digester technology itself as well as the infrastructural components. As mentioned earlier, the infrastructural components of the biogas system are the components that facilitate the delivery of biogas to the user and conveyance of feedstock in and out of the digester. The infrastructural components include the following; biogas pipelines, sewer pipelines and finally accessories such as the gas stove and valves at required positions.

The anaerobic digesters at NLM were analysed and issues were identified within the technology with the aim of optimising the technology. A GA5000 gas analyser (Figure 3-4) was used to test the quality of gas at each digester that was still producing gas to ascertain whether each was still operational.

Figure 3-4: Field Setup for Gas Sampling of household Digesters.

Infrastructural components were critically analysed at each household biogas system during site visits. The scope of the "SANEDI Refurbishment Project" allowed for immediate solutions to the identified issues. Therefore, these immediate issues within the systems were rectified and recommendations to avoid failure in the future were provided with respect to each issue that was not rectified.

3.7. (B) Anaerobic Digestion Process System Implementation at Five ECDCs in NLM

3.7.1. Preliminary desktop investigation

A preliminary desktop study was conducted to find out how an anaerobic digestion process system can be optimised to perform satisfactorily. The study led to the development of the flow chart shown in Figure 3-5, overleaf.

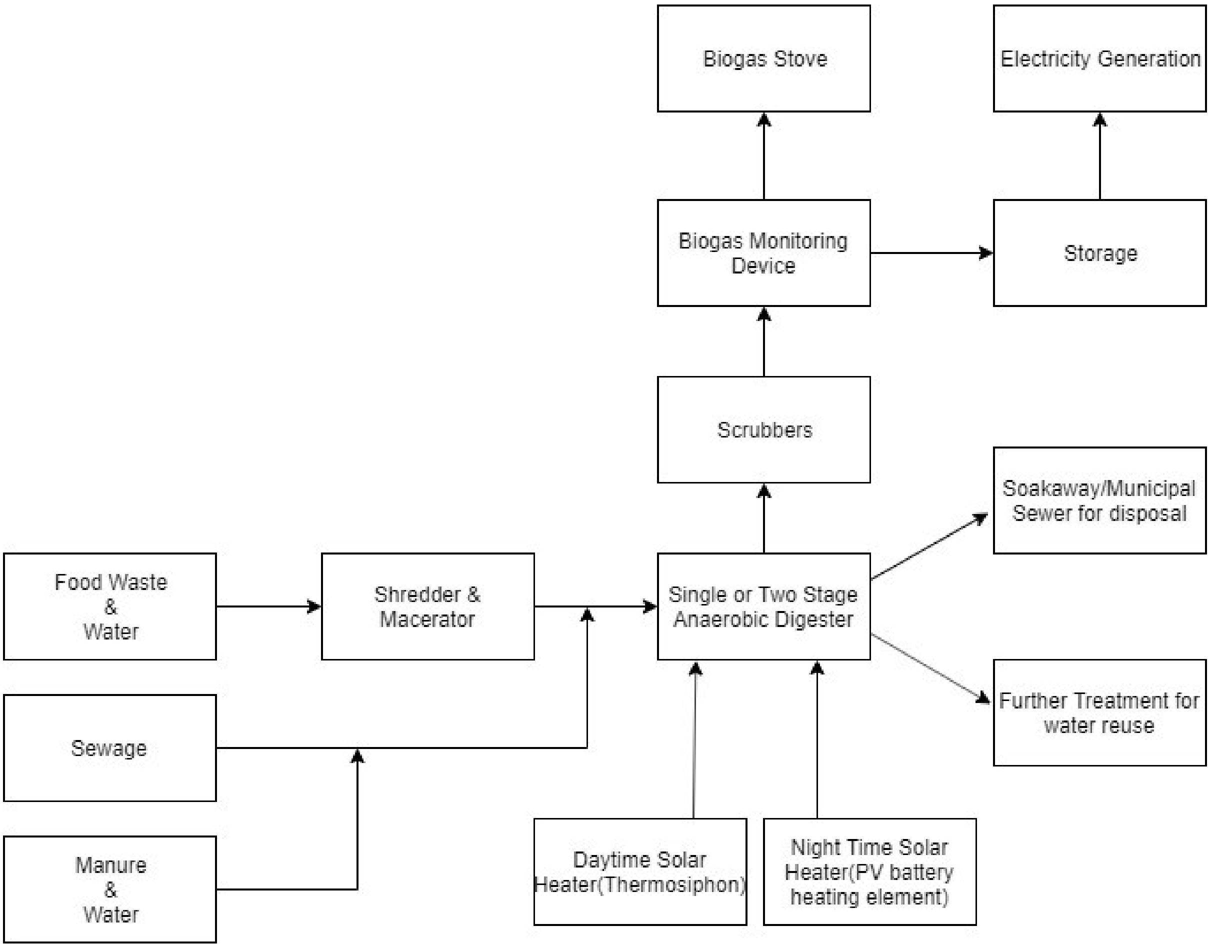

Figure 3-5:Flow Chart showing the Components of a Small or Medium Scale Anaerobic Digestion Process System

The steps illustrated, in Figure 3-5, above show that food waste requires shredding and maceration, for optimal digestion, while the other waste streams shown can be fed to a digester without the aforementioned processes. In addition, especially when dealing with food waste, a two stage system would perform most optimally as it enables the two main processes (acid forming and acid consuming) to occur independently and thus enable the two main bacterial groups to perform at their optimal conditions.

As mentioned earlier, temperature is a very important parameter and optimal temperatures can be achieved by providing additional heat to the digester. To reduce heating requirements, small scale digesters can be installed underground to take advantage of the earth's insulative properties. Regardless however, additional heat will be required in order to reach mesophilic temperatures, which are ideal for small scale purposes. In order to sustainably achieve heating requirements, solar energy can be incorporated. Solar energy can be incorporated using a thermosiphon system for direct heating and using photovoltaic cells to store backup energy for heating in absence of direct solar energy for a thermosiphon heating which predominantly occurs at night.

Biogas collected from the digester will require purification to remove impurities such as Hydrogen Sulphide(HS), water vapour and carbon dioxide, more critically if the gas is to be used for electricity generation. Biogas scrubbing for cooking purposes is not critical but can be advantageous for corrosive biogas stoves by reducing H_2S and water vapour content. H_2S provides an indication of leaks since it has pungent smell. However, H_2S can be dangerous to human beings, especially children, therefore, biogas scrubbing should still be considered to reduce it potential detrimental effects (Agency for Toxic Substances and Disease Registry, 2014).

A biogas monitoring device is important to monitor gas quantity and quality. The quantitative and qualitative monitoring can be used to evaluate the performance of the digester. Remote biogas monitoring devices, if financially viable, can be implemented to monitor sites that are far from the person who will monitor (Chen and Chu, 2016).

Provision of a resistance mechanism can be used to exert pressure to the gas if it is stored in bags, for example through additions of weight to the storage bags. This requirement, however, may not be critical if the digester is designed to provide consistent pressure to the gas such as some CFDD designs. The requirement is most critical if the generated biogas is to be used for electricity generation (Mir et al., 2016). Pressure provision can be incorporated using a gas holder that contains air between a double membrane to provide pressure to the stored gas (Figure 3-6).

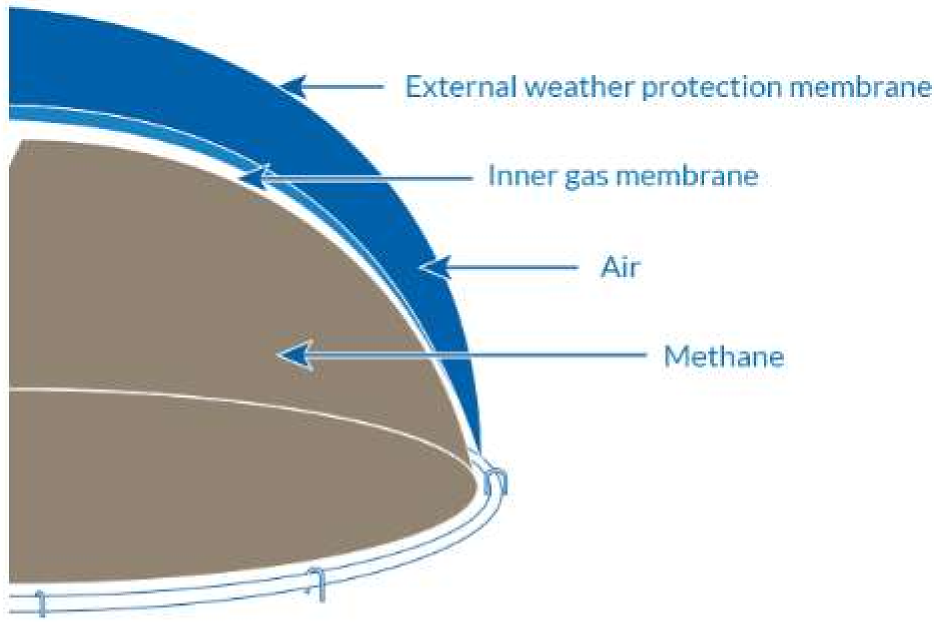

Figure 3-6:Double membrane gas holder

Lastly, the digestate produced from the process can be disposed of into a soakaway and thereafter the digestate can be directed to a garden to act as a fertilizer. If water from the digestate is required to be reused, further treatment will be required such as an aerobic treatment to remove the accumulated ammonia and a form of disinfection to eradicate pathogens, if necessary.

With respect to the sites, the flow chart shown in Figure 3-5, and the overall project, was amended such that it could suit the budget constraints, operation and maintenance considerations.

3.7.2. Site Selection

Possible sites in NLM were selected with the permission and assistance from ward counsellors who are in charge of the wards at NLM. Each site was visited and assessed physically to obtain relevant information. Information that could not be attained physically was obtained by use of interviews. The following criteria was used to select sites and presented as shown in figure to record information during site visits:

- Availability of feedstock; the primary source of feedstock was faecal sludge and food waste generated by the users of the ECDCs as well as cow dung from the surrounding areas. The quantification of food waste and human excreta was performed using population data and average attendance data. The quality of all feedstock was investigated using laboratory tests.
- Availability of water; Water is important for anaerobic digesters and therefore it was important to identify or provide reliable water sources for each ECDC. This was investigated physically at the sites and using information from the interviews
- Presence of food gardens; the presence of such gardens was also considered so that the digestate generated could be of value as a fertilizer for the gardens if any were present
- Management capability; Lastly, one of the major causes of anaerobic digester failures is the maintenance of the systems. Therefore, the management at each ECDC was qualitatively assessed to show their willingness to participate in the operation and maintenance of the digester systems.

3.7.3. Technology Selection

Options for the technology to be used on the sites were considered. Technology required for the sites included the digester itself, which is most relevant to the study, as well as toilet systems and water storage systems, where required. The anaerobic digester was selected after a review of available digester technologies as shown in sections 2.8 and 2.13. All the technology was selected in consideration of the cost, performance, durability, compliance with relevant codes and most importantly how easily it would be adopted and maintained by the users.

3.7.4. System Design

Finally, after all the aforementioned criteria, the design process was begun with the aim of creating an ideal and practical model of biogas provision to the users. All the components of the system including toilet systems were carefully selected and designed to enable biogas provision with the least likelihood of failure in terms of technical, social and the economic aspects.

3.7.5. Project Implementation

After all efforts were made to derive an optimised anaerobic digestion process system for the ECDCs that fit the available budget, a scope of works was drawn up, required materials were procured and construction was begun.

3.7.6. Operation, maintenance and monitoring

A plan was drawn up for the feeding of the digesters. This was derived from literature and BMP tests performed on the main available feedstock for the digester.

An operation and maintenance plan was also generated and provided to the users. This was the essence of investigating the leadership qualities of the users such that they can be responsible enough to perform the operation and maintenance activities to enable optimal performance of the digester systems.

3.8. Feedstock Investigation

An investigation on the available feedstock for the five ECDCs and the households was performed in order to assess their behaviour during anaerobic digestion and their biomethane potential. Available organic waste collected at NLM were taken to be representative. Other characteristics of the feedstock that were obtained provided information about how the feedstock may behave when co-digested.

3.8.1. Sampling

In order to perform investigations on the substrates, it was important to obtain representative samples of the available feedstock that could be utilised. Qualitative interviews as well as literature were used to derive the available forms of organic waste that could be used for anaerobic digestion from the selected sites.

With respect to the 26 households, locally available feedstock was concluded to be sufficient based on interviews and site investigations. It was ascertained through interviews that the household digesters were fed mainly with cow dung, food waste and sewage from toilet connections. It was observed that the digestate from the digester was left to overflow onto the adjacent ground which posed a health concern. Therefore, representative samples of digestate were obtained with the aim of assessing their extent of pathogen pollution and COD. The digestate samples were obtained from a digester that was fed with predominantly black water, food waste and cow dung as well as one that was fed with only cow dung and food waste. The samples were representative with respect to the households and have been presented in table below. Sample Identification(ID) nomenclature was assigned to each sample as shown in Table 3-2.

Table 3-2: Digestate Samples and their Sources

Sample Type (Sample ID)	Source	Description of Source
Digestate 1 (DG1)	Zuma household	Sample obtained from digestate tank of digester predominantly fed with black water but also food waste and cow dung
Digestate 1 (DG2)	Mlangeni household	Sample obtained from digestate tank of digester fed with food waste and cow dung

The locally available feedstock for the ECDCs included; human excreta, food waste and cow dung from neighbouring sources. It was not possible to obtain a sample of food waste from the ECDCs in time for the feedstock investigation. Therefore, using the meal schedule shown in Figure 7-1, Appendix B, a food waste sample was prepared by collecting some food waste from a nearby food shop. The sample of food waste consisted of predominantly maize mill but also contained white rice, meat and beans. The sample of human excreta was obtained by leaving a bucket at one of the ECDCs for its collection. One of the personnel at this ECDC was requested to collect human excreta (urine and faeces) from the children and transfer it into the bucket. Cow dung was obtained from a field within the NLM area. The samples were obtained as shown in Table 3-3. Similarly, Sample Identification(ID) nomenclature was assigned to each sample.

Table 3-3: Selected Samples And Their Sources

Sample Type (Sample ID)	Source	Description of Source
Human excreta (HE)	Children at Sphumelele ECDC	One of the five selected sites aimed to benefit from the project
Cow Dung (CD)	Nomanini Live Stock	Livestock dealership in close proximity to the ECDCs
Food Waste (FW)	Food shops	Food shop in Durban that cooks the same food eaten at the ECDCs
Digester Slurry(Inoculum) (IN)	Ngcobo Household	Anaerobic digester at one of the 26 rural biogas household beneficiaries

3.8.2. Preparation of samples

The samples to be tested each varied in terms of particle size. Therefore, to enable homogeneity of the samples during tests that were performed, a shredder was used to grind all the samples down to a fairly uniform particle size prior to testing.

3.8.3. Quantification of feedstock

It was important to estimate the quantity of feedstock required for the biogas systems at the ECDCs. The population at each ECDC would govern the amount of human excreta and food waste generated. Therefore, the quantity of human excreta and food waste was generated using the average amount produced by each student and this was multiplied by the average attendance each day. It was not possible to quantify cow dung but desirable numbers of cows were observed in close proximity to all the ECDCs.

The quantity of food waste was estimated by instructing the personnel to weigh the amount of food waste generated each day, over a number of days, and note the respective daily student attendance. Table 7-1, Appendix B shows the data collected from this exercise. It was not possible to weigh the amount of human excreta generated each day. Therefore, suggestions by Rose et al. (2015) were used to estimate the amount of human excreta produced each day as well as the stool frequency. It was assumed that each student defecates once every day, according to Rose et al. (2015), at the ECDC and this was backed up by information during participatory observation.

3.8.4. Characterisation Tests

The chemical composition of a substrate can be estimated using characterisation tests. The disparity and abundance of possible feedstock necessitate detailed characterisation tests in order to investigate and predict their behaviour during anaerobic digestion (Steffen et al., 1998). Different characterisation methodologies exist with the aim of finding out the content of each important chemical parameters (Fulford, 1988). The "Standard Methods for the Examination of Water and Wastewater" is the commonly used reference for characterisation tests (Eaton et al., 2017).

All characterisation tests were performed in triplicate and hence were reported with their respective standard deviations. The essence of the standard deviation is to assess the accurateness and precision of the tests. All tests were performed using respective instruments. Rosato (2017) uses Figure 3-7 to describe the essence of accurateness and precision using dots about a centre point. A measuring instrument must be accurate and precise[10].

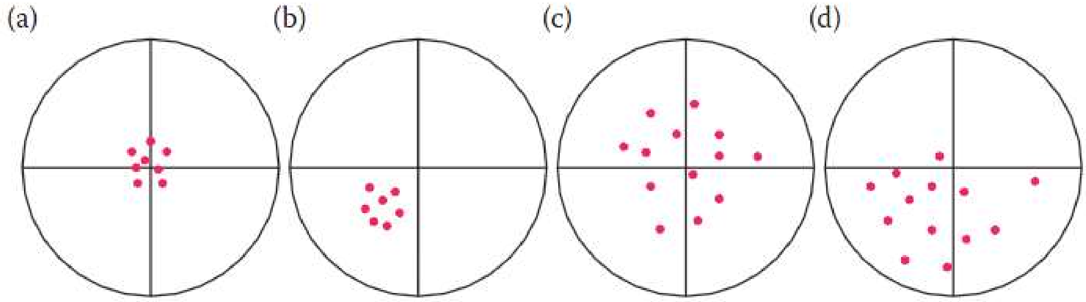

Figure 3-7: (a)Accurate and Precise. (b)Precise but not accurate. (c)Imprecise. (d)Imprecise and Inaccurate (Rosato, 2017).

The characterisation tests executed on all the samples were done with respect to the "Standard Methods, 2nd Edition, 2005" (Eaton et al., 2017) besides the C/N ratio and pathogen indicator tests. The aforementioned tests were sent to nearby laboratories for testing The characterisation tests were performed on different samples at different times but the same procedure was followed each time as described in the sections that follow.

All samples were tested in triplicate. The laboratory characterisation tests that were performed include:

- TS/VS
- COD

[10] For detailed information on the subject; refer to *"Managing Biogas Plants_A practical Guide*" by Rosato MA (2017) *Managing Biogas Plants: A Practical Guide.* CRC Press.

- BOD_5
- RI_7
- C/N ratio
- VFA/TA ratio (Food Waste)
- Pathogen Indicator Tests (*Faecal coliforms, E. coli, Faecal streptococcus* and *Enterococci*)

3.8.4.1. Total Solids (TS), Volatile Solids (VS) and Moisture Content (MC) tests

TS is the quantity of residual matter of a substrate after drying in an oven at 110°C. It represents the amount of solid matter in a substrate. VS is the quantity of residual matter of a substrate after heating at 500°C; this parameter is representative of the amount of organic matter present in the solid fraction of a substrate. The apparatus used for the tests include:

- Mass balance scale
- Furnace
- Pincers
- Desiccators
- Crucibles
- Oven
- Metallic tray

Sample were placed into respective crucibles and then placed inside an oven at 110°C overnight, removed in the morning and left in a desiccator to cool. After cooling, the crucibles were weighed and values were recorded. The TS content was calculated by dividing the weight of the dried residue by weight of the wet sample and expressed as a percentage (Equation 3-1). The crucibles were thereafter placed into a furnace at 500°C with the aim of attaining the VS content. The VS content was calculated using (Equation3-2). The MC can be calculated by subtracting the %TS from 100%. Figure 3-8 illustrates the mass balance that was used as well as some of the samples arranged in triplicate.

Equation 3-1: %TS

$$\%TS = \frac{(A-B)\times 100}{(C-B)}$$

Equation 3-2: %VS

$$\%VS = \frac{(A-D)\times 100}{(A-B)}$$

Where,

A= Weight of oven dried residue + crucible

B= Weight of crucible

C=Weight of wet sample + crucible

D= Weight of furnace dried residue + crucible

Figure 3-8: Mass Balance and some Samples arranged in triplicate

3.8.4.2. pH Test

The pH represents the amount of hydrogen ions present in a substrate. It gives an estimation of the acidity or alkalinity of a substance The pH test was performed using an "Orion 410A" device with a probe. The device was calibrated using solutions of pH10, 7 and 4. A sample was placed with a stirrer inside a beaker into which the probe was placed to take readings of pH as illustrated in Figure 3-9.

Figure 3-9: Setup for determining pH

3.8.4.3. Biochemical Oxygen Demand test (BOD)

The Biochemical Oxygen Demand (BOD); The quantity of oxygen consumed during the microbial degradation of organic material is known as the biochemical oxygen demand (Peavy et al., 1985). The BOD is quantified by determining the amount of oxygen consumed by a sample as it degrades inside an airtight container at controlled conditions in a specific time duration. The BOD test measures the amount of oxygen required to completely degrade organic material and thus a BOD test provides an indication of the biodegradability of a substance. There are two phases of decay in the BOD test: a carbonaceous and a nitrogenous phase (see Figure 3-10 below).

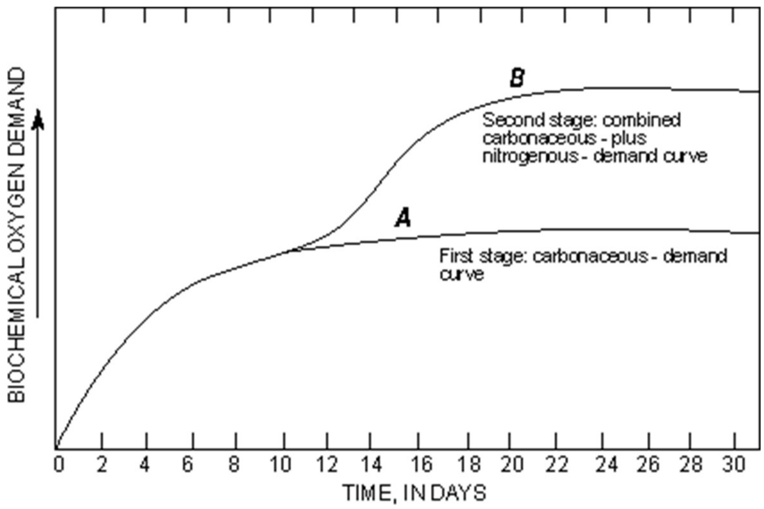

Figure 3-10:Carbonaceous and Nitrogen Oxygen Demand (Peavy et al., 1985)

The carbonaceous phase represents the amount of oxygen required for the conversion of organic carbon to carbon dioxide while the nitrogenous phase, shows a combined nitrogenous and carbonaceous demand. The nitrogenous demand is a result of organic nitrogen conversions. The five-day test is often referred to as a BOD_5 test. Some oxygen may be used up to convert nitrogenous compounds to more stable forms during the five-day test and hence a chemical for example Allyl-Thiourea (ATH) is usually added to inhibit oxygen consumption by nitrogenous compounds.

The five-day test is often referred to as a BOD_5 test. Some oxygen may be used up to convert nitrogenous compounds to more stable forms during the five-day test and hence ATH drops were added to inhibit oxygen consumption by nitrogenous compounds. The demand that was measured was therefore the carbonaceous biochemical oxygen demand. The test is specifically suited to liquid samples and was performed on the more liquid samples.

The required amount of sample was measured in a measuring cylinder and poured into bottles which were then sealed by means of an oxytop head and placed into an incubator for five days. A remote was used to retrieve the information from the oxytop heads after 5 days. The bottles, oxytop heads and BOD sensor remote are shown in Figure 3-11.

Figure 3-11: Apparatus setup for the BOD test

3.8.4.4. Respiratory Index Test

A BOD_5 and respiratory index test both provide indications of the biodegradability of a substance however the latter is suited to predominantly solid samples and hence was performed on the more solid samples. The respiratory index tests were performed for a seven day period according to the protocol developed by Eaton et al. (2017).

During the experiment, fifty grams of each sample was measured and placed into flasks as shown in Figure 3-12 below. For some samples, flasks of 1.5 volumes were used while flasks of one litre volumes were used for the rest based on availability of the flasks. For each of the samples in the flasks, 4ml of water and 20 drops of potassium hydroxide were added to the flasks. The bottles were then sealed with an oxytop head and placed in an incubator. The bottles, oxytop heads, mass balance, RI sensor remote and some of the flasks used are shown in Figure 3-12. A respiratory index sensor was used during the entire seven-day period of the experiment and read at the end of the seven days.

Figure 3-12: Apparatus setup for Respiratory Index Test

3.8.4.5. Chemical Oxygen Demand (COD) Test

As mentioned earlier, the Chemical Oxygen Demand is defined as the quantity of a specific oxidant that reacts with a sample under controlled conditions (Eaton et al., 2017). It is a measurement of the quantity of oxygen necessary for oxidation of soluble and particulate organic matter (Tayler, 2018). The COD is indicative of the amount of biodegradable and non-biodegradable organic matter in a substrate as shown by Figure 3-13.

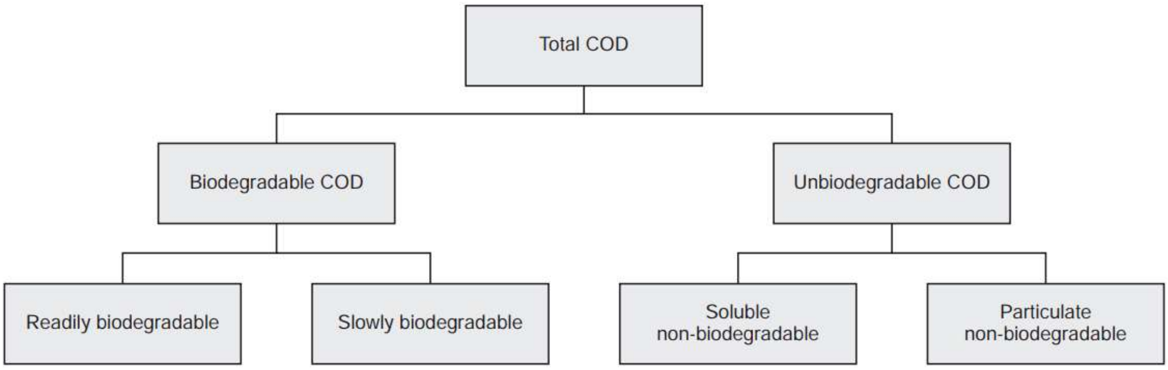

Figure 3-13: Description of Chemical Oxygen Demand

Both organic and inorganic constituents of a sample are subject to oxidation however the organic component is dominant. To distinguish between the organic and inorganic oxygen demand, one needs to use other tests. In this context, the BOD test was used to distinguish between the two oxygen demands. The most ubiquitous method of COD measurement is known as spectrophotometry (Rosato, 2017).

The basic principle, which is sketched in Figure 3-14, is as follows: a liquid under test is dosed into a vial, reacts chemically with the latter's content, changing the solution's colour; after a high temperature thermal reaction, the vial is introduced into a spectrophotometer, between a light source of given wavelength and the light sensor; the difference between the light intensity across the vial and a reference(blank) is then processed by a microprocessor and values can be manipulated to obtain the COD (Rosato, 2017). In addition Rosato (2017) suggests that samples of relatively high solid content must be diluted to be suitable for a COD test as the test was developed mainly for liquid samples.

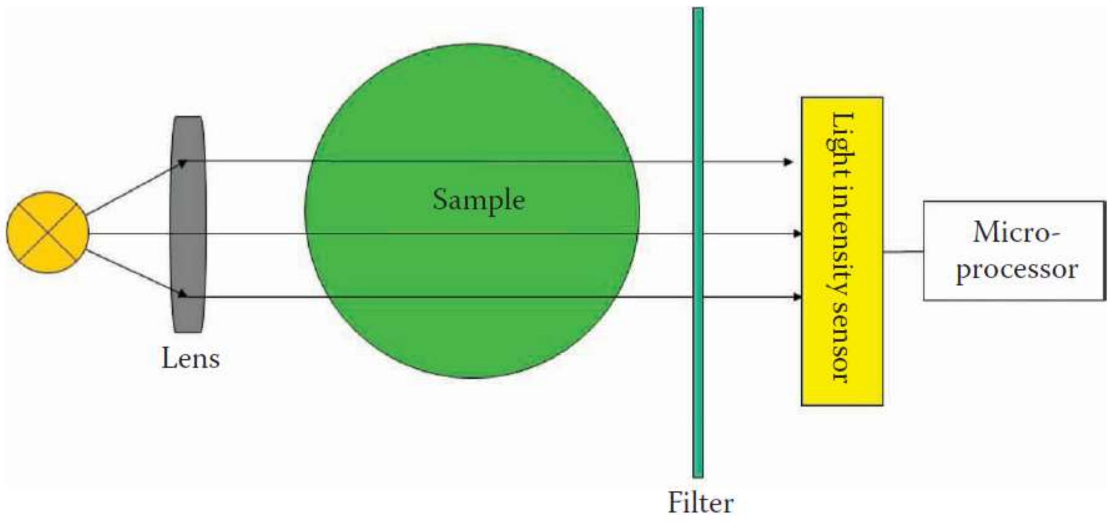

Figure 3-14: Principle of a COD test (Rosato, 2017)

The COD test was performed on the respective samples using the following chemicals and apparatus:

- KHP solution
- Spectrophotometer instrument
- Pipettes
- COD Digester
- Potassium dichromate solution
- Concentrated Sulphuric acid solution
- Test tubes
- Beakers

The COD analysis was performed as follows:

- The required samples were ground and diluted to make them suitable for the COD test
- 0.2ml of each sample was then added to a set of test tubes into which 2.3ml of distilled water was added.
- Thereafter, 1.5ml of potassium dichromate and 3.5ml of concentrated sulphuric acid was added to the test tubes.
- Three samples of KHP were assembled with 1.0ml of KHP, 1.5ml of water, 1.5ml of potassium dichromate and finally 3.5ml of acid
- Four blank samples were similarly prepared with 2.5ml of water, 1.5 ml of potassium dichromate and 3.5ml of sulphuric acid.
- The samples were all then placed in a COD digester for 2 hours after which they were placed in a spectrophotometer.
- A standard wavelength of 600nm was used to measure the spectrophotometric values
- The absorbance value readings were taken to calculate the COD concentrations.

3.8.4.6. Volatile Fatty Acid /Total Alkalinity (VFA/TA) ratio test.

Volatile Fatty Acids to Total Alkalinity (VFA/TA) refers to the ratio of volatile fatty acids to alkalinity in a substrate. According to Rosato (2017), it may sometimes be referred to as the FOS /TAC; FOS and TAC stands for *Fluchtige Organische Sauren* , which means VFA in German, and *Totales Anorganisches Carbonat* ,which means TA in German, respectively. This parameter is especially important as it shows the buffering capacity of a substrate (McDonald, 2006). In addition to being a characterisation parameter, it can also be used to monitor anaerobic digester performance. According to Rosato (2017), the VFA/TA ratio of a substrate is acceptable within the range of 0.3-0.4. A ratio of greater than 0.5 is indicative of impending digester failure. Reduction of loading rate can lower the VFA/TA ratio. Table 3-4, below, describes some VFA/TA ratios together with their indications and actions to be taken with respect to those indications.

Table 3-4: The Original FOS/TAC Table According to Lossie and Putz (2009)

FOS/TAC Ratio	Indication	Actions to be Taken
>0.6	Excessive organic load	Stop feeding the digester
0.5–0.6	High organic load	Reduce feedstock input
0.4–0.5	The digester is at the limit	Monitor the digester carefully
0.3–0.4	Ideal conditions for the production of biogas	Keep feedstock input constant
0.2–0.3	Insufficient organic load	Increase gradually the feedstock input
<0.2	Extremely low organic load	Increase quickly the feedstock input

The TA/VFA was determined by titrating a filtered sample with sulphuric acid to exact pH values of 5 and 4.4 as proposed by Weiland and Rieger (2006). The volume of sulphuric acid required to achieve the pH values was logged and the TA/VFA ratio was calculated using equation

Equation 3-3:Formula to calculate VFA/TA

$$\text{TA/VFA}=\frac{(VpH4.4-VpH\ \ )\times\frac{20}{Vsample}\times\frac{Acid\ Normality}{0.1}\times1.66-0.15)\times500\times Vsample}{0.5\times Acid\ Normality\times VpH5\times Molar\ Mass\ of\ Calcium\ Carbonate\times1000}$$

3.8.5. Biogas Yield and Bio-methane Potential Test

Biogas yield is the quantity of biogas, while bio-methane potential(BMP) refers to the experimental maximum quantity of methane that is generated, by a substrate during anaerobic digestion in a given time (Rosato, 2017) . According to Rosato (2017), sometimes it may be followed by a suffix, which indicates the duration of BMP test, for example, BMP_{20} refers to a 20 day BMP test; if the suffix is not added, it is commonly assumed that the test was run for 30 days. The BMP of a substrate can be theoretically calculated using a substrates chemical composition or it can be determined in a laboratory. The theoretical BMP of a substrate is often unreliable as it nearly impossible to achieve a theoretical BMP in reality and therefore a laboratory BMP test is often performed (Rosato, 2017). According to Rosato (2017), it should be a rule to distrust theoretical BMP values to predict behaviour in reality ; in rare cases, the activity of a digester's bacterial ecosystem may sometimes reach the theoretical BMP under laboratory conditions but it will rarely correspond to a real biogas plant's conditions.

The BMP of a substrate is determined in a laboratory by mixing the organic substrate with inoculum inside a closed vessel at a set temperature for a set time duration while recording gas quantity and quality. According to Wojcieszak et al. (2017), inoculum is a substrate that is used as a source of anaerobic microorganisms to start the process. Various substrates can be used as inoculum but the choice and amount of inoculum determines how long the digestion process will take to begin. Microorganisms within the inocula may have to acclimatise to the new environment to which they are transferred. If the environment to which the inocula is transferred is very similar to its original environment then the acclimatisation process will occur quickly and conversely if the two environments are significantly different, then acclimatisation will occur slowly. (Liu et al., 2017b). Commonly used inocula include cattle rumen, cow dung or substrate from an already operational anaerobic reactor (Wojcieszak et al., 2017). Ruminant dung (such as cows and buffalos) is suitable inoculum for digestion of cellulolytic substrates while monogastric (such as pigs and chickens) dung is suitable for digestion of protein and fat rich substrate. Rosato (2017) suggests that inoculum for a BMP test must be sampled from an already operational digester.

During a BMP test, gas quantity is measured periodically and analysed for its methane content and thus the biomethane potential is obtained and usually expressed in SI units such as Nl/kgVS, Nml/kgVS or Nm^3/tonVS (COD may be used in place of VS)[11]. The gas volumes are usually normalised to standard temperature and pressure to enable comparison because gas volumes are dependent on temperature and pressure according to the ideal gas law (Liotta et al., 2013). The ideal gas law is a physical law that describes the relationship of quantifiable properties of an ideal gas where the product of its volume and pressure is directly proportional to the product of the its number of moles, gas constant (R) and temperature (Liotta et al., 2013). Biogas and biomethane are known to behave as ideal gasses (Villegas Aguilar, 2015).

Various methods to measure the biomethane potential of a feedstock have been proposed by practitioners such as Filer et al. (2019) which all basically involve the incubation of a sample inside an airtight reactor(usually a bottle) within a temperature controlled water bath and attaching it to a gas collection and measurement mechanism. According to Rosato (2017) gas collection and measurement methods may be volumetric(at almost constant pressure) or barometric(at constant volume) which are both derived from the ideal gas law. Barometric methods are more suited to aerobic tests, for example a BOD test, and were indeed born for

[11] Refer to section 2.9.2.

such tests but have been readapted for BMP tests. Gas measurement is achieved using devices that can either be self-constructed or purchased as a pre-assembled kit. The latter is preferred because it is usually more accurate and in addition, self-constructed setups require procuring of components, assembly and calibration which can be a tedious and error-prone process. However, pre-assembled kits are more expensive and sometimes more difficult to obtain. For example, Rosato (2017) prescribes the *Automatic Methane Potential Test System*(AMPTS), which is more ubiquitous, and the Bio Reactor Simulator(BRS) as the most modern, accurate and precise instrument for BMP measurement, however both instruments are not available in South Africa (Bioprocess Control Sweden, 2016) and therefore would require importation. An example of a BMP setup is shown in Figure 3-15; however other setups may be employed. Other methods of gas collection may be used in place of a eudiometer for example gas bags and flow meters. It is important to note that the volume of reactor does not affect the error in a BMP test unless one is dealing with very refractory substrates such as biodegradable plastics (Rosato, 2017).

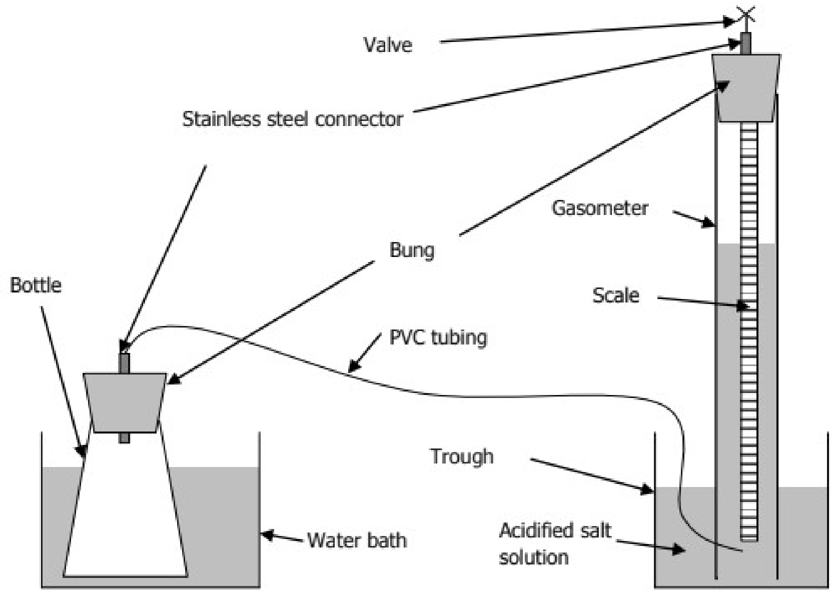

Figure 3-15: Typical volumetric BMP test setup (Walker et al., 2010)

There is currently no standard protocol to perform a BMP test. A workshop that took place in Leysin, Switzerland, attended by forty scientists from thirty laboratories across the globe, was intended to optimise a common solution to the problem of BMP inconsistency evidenced by results that were presented (Holliger *et al.*, 2016). The major outcome of the workshop was the consensus of a need for BMP test standardisation. However, automated systems to measure the BMP of a sample exist but are usually expensive, though they may provide more reliable results (Filer et al., 2019). However, BMP test data is associated with variability among results from different authors , according to Rosato (2017). Rosato (2017) attributes the great variability to the chemical composition and grain size of a feedstock both of which are impossible to tabulate because they are dependent on the activity and biodiversity of the inoculum, the reactor's geometry, mixing intensity, presence or absence of bio-catalysts and so on. The great disparity in BMP values has often led researchers to question the test protocols (Rosato, 2017). For instance, Raposo et al. (2011) conducted a study on 18 laboratories who determined the BMP of a 100% biodegradable and pure substance with a well-defined theoretical BMP- starch. The results are shown in Figure 3-16 below. Figure 3-16 shows that the causes of variability of BMP tests can be quite elusive considering the fact the tested sample was a pure substrate and the tests were performed by expert laboratory operators in controlled conditions. It can preliminarily concluded that BMP does not only depend on the chemical composition of the substrate, but also on the inoculum, sample preparation and numerous other factors (Raposo et al., 2011).

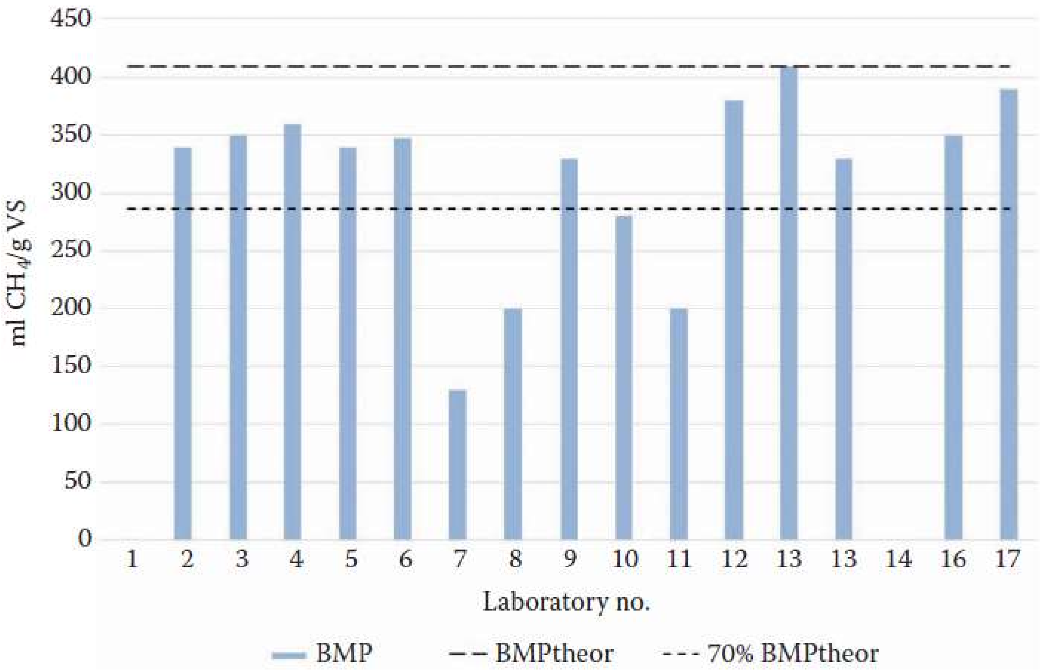

Figure 3-16: The BMP of starch, as measured by 18 different laboratories (Raposo et al., 2011)

According to Rosato (2017), a common joke within the scientific world goes, "under perfectly controlled laboratory conditions, any living organism will behave in a way completely different from the researcher's initial hypothesis" (Rosato, 2017). Jokes aside, it is perfectly true and normal to expect variability in BMP results that were performed in exactly the same manner, but results may provide an idea of a feedstock's behaviour. Some BMP values of cow dung, food waste and human excreta from different authors have been shown in Table 3-5. It is important to note that despite human excreta's relatively high BMP, it may not be viable at a household level due to low daily excreted mass (Mang, 2010)

Table 3-5: Typical BMP value from literature

Substrate	BMP(Nl/kgVS)	Reference
Cow dung	382	Widiasa et al. (2009)
	179	Goberna et al. (2010)
	620	Cavinato et al. (2010)
	250	Sathianathan (1975)
	240	Rosenberg and Kornelius (2017)
	575	Sawyerr et al. (2019)
Food Waste	297-489	Cho et al. (1995)
	348-435	Zhang et al. (2007)
	489	Heo et al. (2004)
	512	Samson et al. (2018)
	88	Embuldeniya et al. (2017)
	560	Thenabadu et al. (2015)
Human Excreta	360	Del Borghi et al. (1999)
	210	Benetto et al. (2009)
	169	Ngumah et al. (2013)
	290	Mang (2010)
	150	Regattieri et al. (2018)
	433	Gomaa and Abed (2017)
	440	Colón et al. (2015)
	380	

It was important to estimate the biogas yield and BMP of the feedstock in order to investigate the behaviour of each feedstock when analysed in conjunction with the characterisation tests.

The BMP test was performed with respect to a modified BMP test protocol described by Walker *et al.* (2010).

The following steps describe the procedure that was used to determine the biogas yield and ultimately BMP of each sample:

1. Before the BMP test was started, the inoculum was placed in a closed container and left in an incubator almost immediately after collection for one and a half weeks and degassed every two days. This was to reduce the inoculum's contribution to the BMP test values. This procedure was adapted from Rosato (2017)[12]

[12] The importance of this procedure is explained in detail in :*"Managing Biogas Plants_A practical Guide*" by Rosato MA (2017) *Managing Biogas Plants: A Practical Guide.* CRC Press.

2. Three one litre bottles were prepared for each sample to be tested except the samples of human excreta that was placed into 500ml bottles due to insufficient 1 litre bottles.
3. Equations 3-3 and 3-4 were used to calculate the mass of feedstock to be used for the BMP test according to their respective VS content. Table 3.6 shows the masses of feedstock and inoculum used during the experiment.

Equation 3-4: Mass of feedstock required for BMP test

$$\text{Feedstock required (g)} = \frac{400}{1+(\frac{R\times VS(feedstock)}{VS(inoculum)})}$$

Where the inoculum to substrate ratio, R= 2:1

Equation 3-5: Mass of inoculum required for BMP test

Inoculum added (g) =400 – feedstock added.

Table 3-6: Mass of feedstock and inoculum used during the BMP test

Sample	Food Waste	Human Excreta	Cow Dung
Mass of substrate added (g)	28.01	64.59	28.87
Mass of inoculum added (g)	471.99	335.41	471.13
Total Mass (g)	500	400	500

4. The pH of each sample was checked and thereafter, samples were weighed, mixed and poured into the respective bottles.
5. The pH of the food waste sample fell below the optimum range and therefore sodium bicarbonate was added arbitrarily each day in an attempt to keep the pH within range. The food waste sample however did not produce any methane during the first trial. This then necessitated a TA/VFA test which also yielded values beyond the optimum range. Therefore, a new BMP test was setup for food waste, at a later stage, and before the test, sufficient sodium bicarbonate was added to the sample until the TA/VFA ratio was within range.
6. All the sample bottles were then placed in a water bath at a temperature of 35°C and purged with nitrogen gas and then sealed with a bung. The setup was left for 15 minutes to allow the headspace to equilibrate.

7. The bottles were then connected to eudiometers using tubing. The inoculum samples were connected to gas bags due to insufficient eudiometers for all the samples.
8. Based on previous BMP test attempts failure due to leaks, all possible points of leakage were blocked off using silicone.
9. The experiment was then left to run for 30 days.
10. Two days after the experiment was started, two of the cow dung samples exploded (Figure 3-17) due to pressure build up in the headspace which was deduced to be insufficient. The bottles for cow dung were then emptied to 500ml and the test for cow dung was restarted. Due to this issue, the food waste BMP test that was started at a later stage utilised a 500ml volume together with three other inoculum samples that were also degassed prior to use.

Figure 3-17:Explosion of cow dung sample bottle

11. During the experiment, the bottles were shaken once every day and gas was extracted and analysed each day using a GA5000 Gas Analyser (Figure 3-18).

Figure 3-18: GA5000 Gas Analyser

12. The water bath was covered with a black plastic cover to maintain a constant temperature and to limit water loss due to evaporation as shown in Figure 3-19.

Figure 3-19: BMP test setup

13. The volume of gas generated each day was normalised and calculated using Equation 3.6 (Walker et al., 2010). The temperature in the room was regulated by an air conditioner that was checked each day for every gas volume reading and the pressure was assumed to be atmospheric pressure each day. The volume of methane was calculated using the percentage methane concentrations obtained from each sample's gas quality measurements.

Equation 3-6: Formula to calculate volume of gas

$$V_{stp} = \frac{T_{stp}A}{T_{atm}p_{stp}}\left(\left(p_{atm} - p_{H_2O}(T_{atm})\right) - \rho_b g(h_t - h_c)\right)h_c$$

Where $p_{H_2O}(T) = 101324.6 \times 10^{z}$

and

$$z = -7.90298\left(\frac{373.16}{T} - 1\right) + 5.02808\log_{10}\left(\frac{373.16}{T}\right)$$
$$-0.00000013816\left(10^{\left(11.344\left(1-\frac{T}{373.16}\right)\right)} - 1\right) + 0.00813289\left(10^{\left(-3.49149\left(\frac{373.16}{T}-1\right)\right)} - 1\right)$$

Where

V – Volume of gas (m^3)

P – Pressure (Pa)

A – X-section of eudiometer (m^2)

T – Temperature (K)

ρ – Density (kgm^{-3})

h – Distances measured relating to the position of the barrier solution

stp, atm, H_2O*, b, t* and *c*

Respectively, the subscripts refer to standard temperature and pressure, atmospheric,

Water, barrier solution, trough and column.

3.8.5.1. Kinetic Model

A graph of cumulative daily gas yield against time in days is plotted using BMP results. The typical shape of a BMP graph is shown in Figure 3-20, overleaf and is characterised by a lag, reactive and unreactive phase.

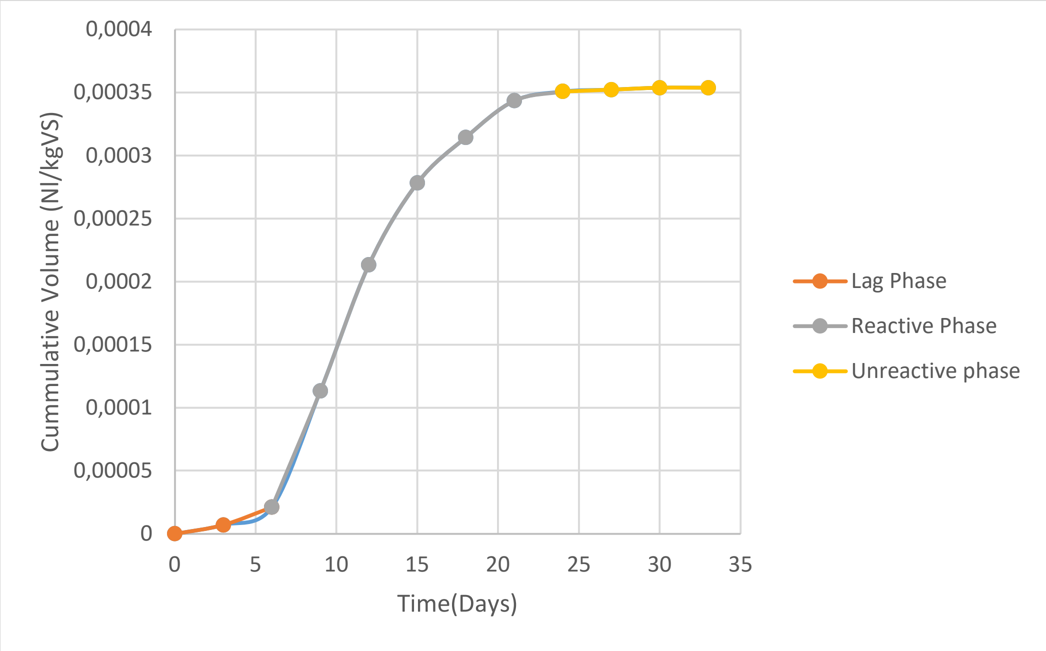

Figure 3-20: Typical Biomethane Potential graph showing different phases

Various mathematical models have been developed to analyse the chemical kinetics of anaerobic digestion and thus derive the bio methane potential of a substrate from its graph. These models include, but not limited to, the modified Gompertz model, the cone model and the exponential model (Velázquez-Martí et al., 2018).

The analysis of both biogas yield and biomethane potential was conducted using the “sigmoid-type modified Gompertz” function. In the Gompertz bacterial growth model, the cumulative biogas and biomethane production *G(t)* over time *t* is expressed by kinetic parameters shown in equation (Zwietering et al., 1990)

Equation 3-7: Modified Gompertz Equation

$$G(t) = P \cdot \exp\left(-\exp\left[\frac{Rm.e}{P}(\lambda - t) + 1\right]\right)$$

The aforementioned parameters, which are represented in Figure 3-21, are:

- *P*: Maximum gas yield (L/gVS)
- R_m: Gas production rate (Nl/day.gVS)
- *λ:* Lag phase duration (days)

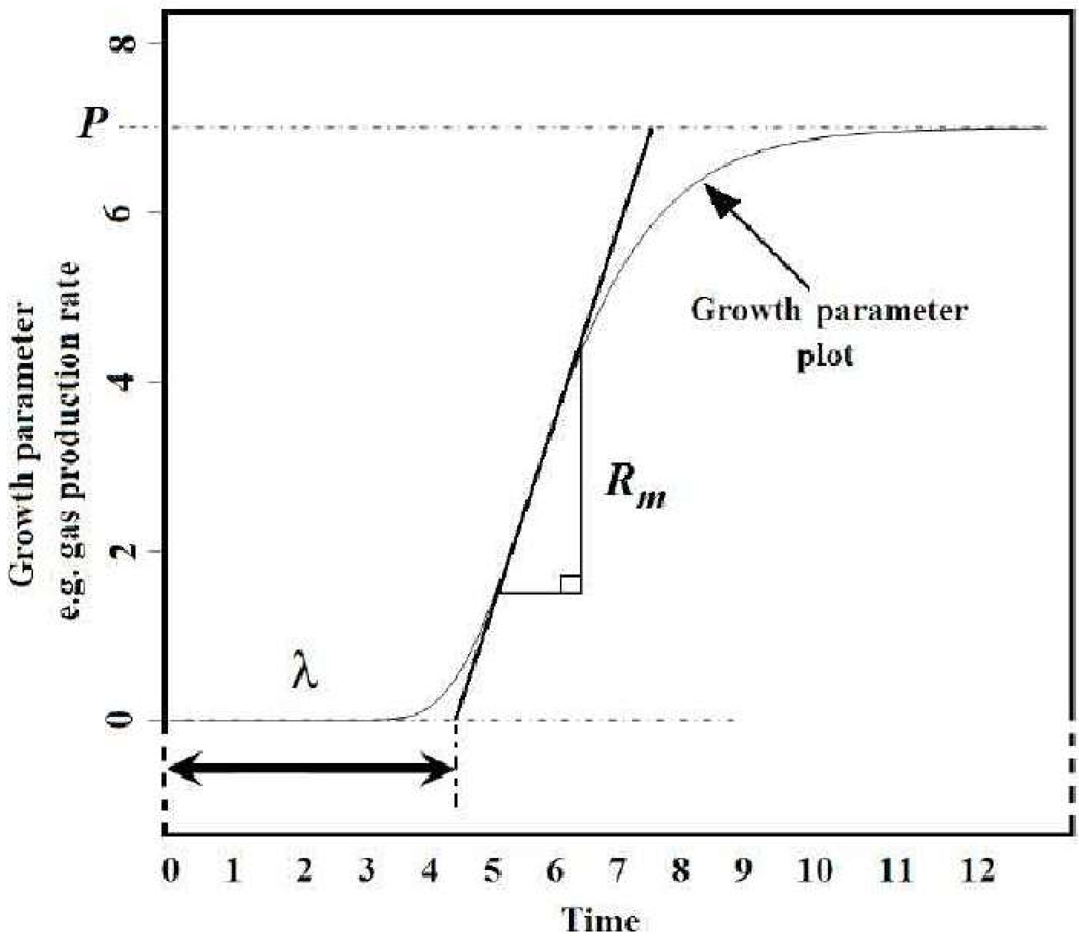

Figure 3-21: Typical parameters illustrated by the modified Gompertz growth curve (Wakadikar, 2013)

The mathematical constant "*e*" within Equation represents Euler's constant which is equal to 2.71828. The experimental data obtained during the BMP test was fitted into the Gompertz equation using MATLAB software to obtain parameters *P,* R_m and λ. The software utilised appropriate statistical parameters, which include: coefficient of determination R^2 and root-mean-squared error *RMSE,* to judge the goodness of fit for each experimental data set.

3.9. Experimental Design for Optimised Anaerobic Digester

3.9.1. Experimental Description

Anaerobic digesters for rural areas are, in most cases, operated at long HRTs and low influent %TS content attributable to limited mixing as well as lack of additional heating. These digesters are therefore associated with large volumes and due to the aforementioned reasons, are limited to a specific OLR. Chinese Dome Digesters have been shown to suit rural communities because of their relatively long lifespan, ease of operation and low maintenance requirements, moreover they form the basis for most prefabricated digester designs.

Therefore, an optimised digester design has been proposed based on the CFDD to be tested against a control. Prototypes were designed, fabricated and tested for a period of 30 days while daily gas quantity and quality was measured.

3.9.2. Design

Major small scale digester designs in South Africa have been reviewed and an optimised prototype has been developed to perform optimally in terms of higher gas volume output and process stability under a high organic loading rate. The optimised prototype has been designed with the expansion chamber and reactive chamber as one unit; this can ease fabrication and assembly. Digester designers have used this concept before especially for prefabricated digesters (Cheng et al., 2014). The expansion chamber is situated above the reactive chamber to enable the gas to be pressurised under the weight of the slurry (An example of a digester in South Africa with such an adaptation is the Puxin Digester that was mentioned earlier).

The digester has been designed with no pipes at the inlet and outlet (rather than a reactor tank, inlet tank and expansion chamber tank which would need to be assembled). A “foam and scum guard” have been installed on each digester to prevent any scum or foam from being released through the gas outlet. In addition, two newly proposed features have been added with the aim of improving the process of anaerobic digestion and thus a blank digester has been designed without these features for comparison. The optimised digester prototype as well as the control have been presented in Figures 3-22 and 3-23 respectively. They have both been designed using acrylic to enable transparency and optimal heat retention. The design and parts of the digesters have been shown in Figures 3-22 and 3-23.

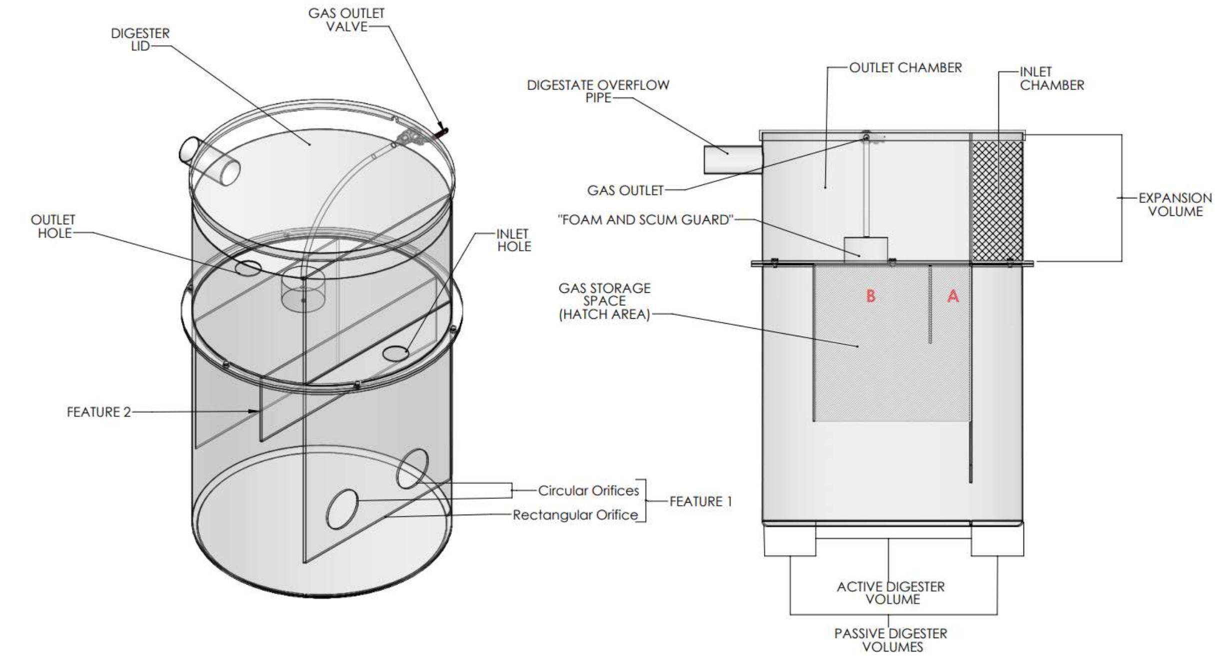

Figure 3-22: Optimised Digester Prototype Design

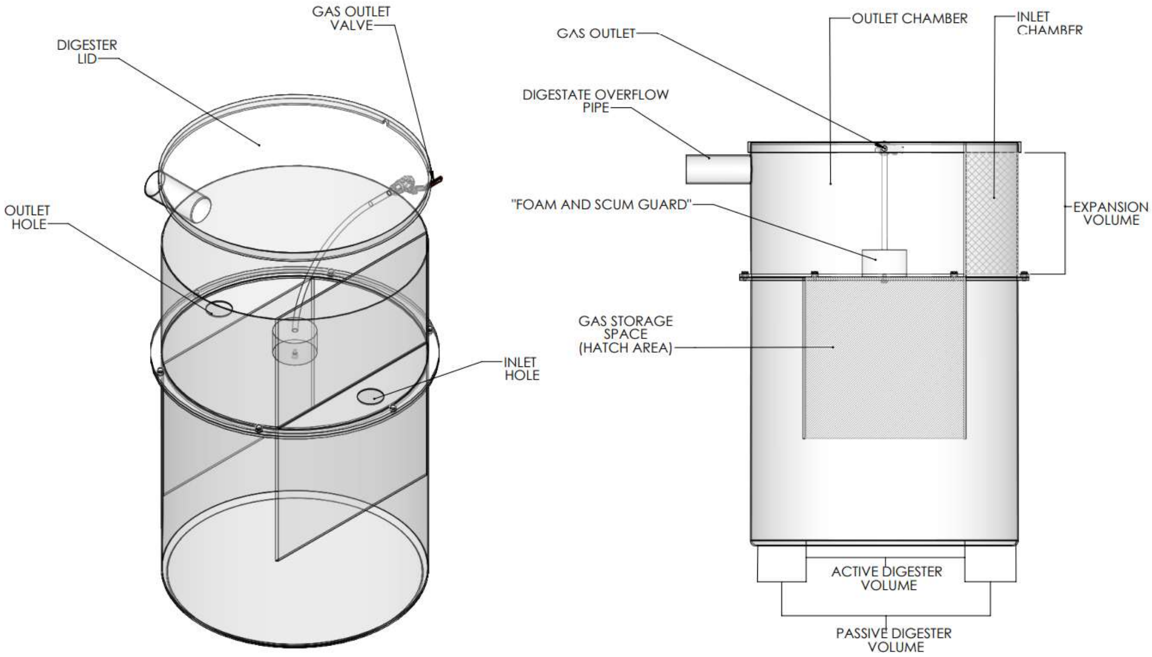

Figure 3-23: Control Digester Prototype Design

In order to optimise the process of anaerobic digestion an investigation into the addition of two features (see Figure 3-24) has been done.

Feature 1 consists of three sub-features (one rectangular and two circular orifices) that have been designed based on simple hydraulic principles with the aim of reducing the flow rate and hence cause temporary retention of the feedstock as it enters the reactive chamber of the digester. The circular orifices have been placed at their position to enable the prototype and control to have the same gas storage space for comparison. Equations 3-7 and 3-8 were used to size the rectangular and circular orifices respectively.

Equation 3-8:

$$Q = \frac{2}{3} Cd.\, b\sqrt{2g}(h2^{\frac{3}{2}} - h1^{\frac{3}{2}})$$

Equation 3-9:

$$Q = \frac{\pi}{4} Cd.\, D^2\sqrt{2gh}$$

Where:

Q- Flow rate

Cd-Coefficient of discharge

b-width of rectangular orifice

D- Diameter of circular orifice

h1 and h2 are shown in Figure 3-24

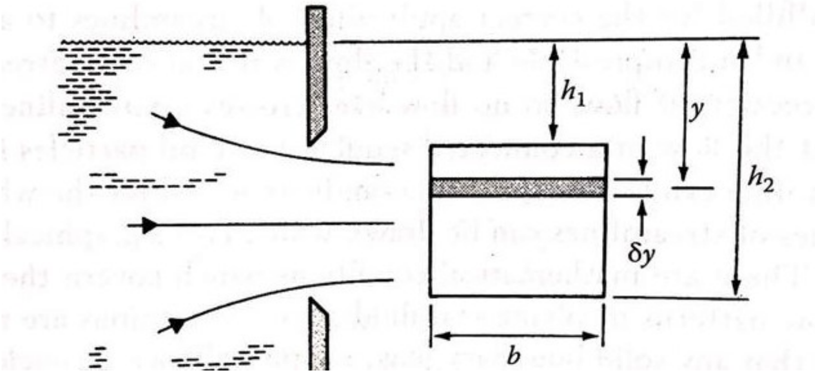

Figure 3-24: Parameters used in Sizing of a Rectangular Orifice

Both equations show that the flow rate through an orifice is dependent on their area. Therefore, this shows that the flow rate through the inlet in the optimised digester will be slower than that of the control. This concept was tested through laboratory experimental iterations with different orifice sizes to prevent clogging while still achieving its purpose. Figure 3-25, below, shows the sections through both digesters to visually present Features 1 and 2 as well as sections A and B.

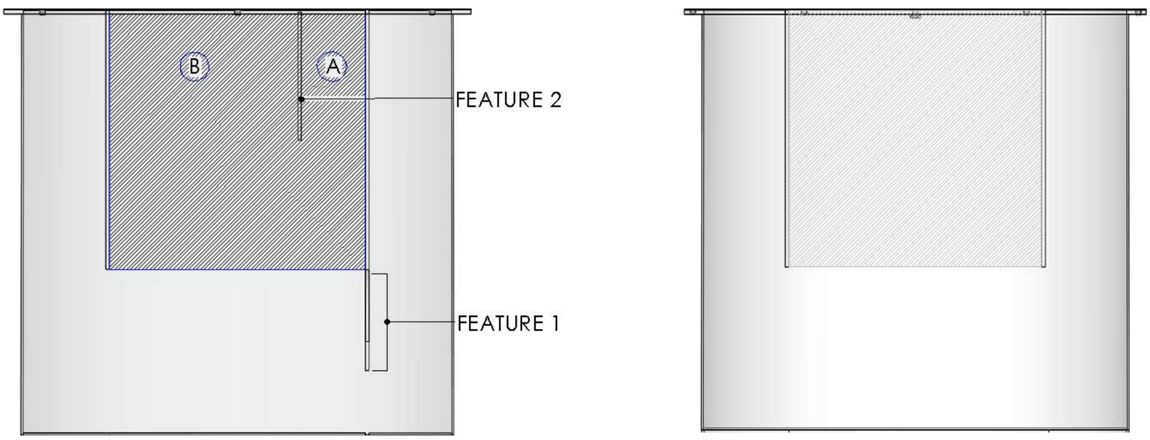

Figure 3-25:Section through optimised digester (left) and control (right)

Hence this temporarily retains the feedstock as it enters into the reactive chamber. The essence of the short temporary retention of the feedstock is to prevent the influent feedstock from immediately mixing with already present digester content during feeding. This is expected to improve the process as it prevents shock organic loads onto the microorganisms. The temporary retention of the slurry also enables the influent slurry to undergo some slight degradation before it is mixed with the already present slurry.

Feature 2 is a baffle has been designed to enable a self-mixing mechanism using some of the produced biogas. The baffle divides the headspace into chamber A and B as shown in Figure above. When biogas is extracted from chamber B, the pressure in the chamber A (without an outlet) builds up causing some gas to escape to chamber B causing mixing. When gas is extracted each time, some residual gas will remain in chamber A. Jegede et al. (2019) similarly investigated a mixing regime caused by a baffle in the headspace and found that the mixing improves biogas performance despite the residual gas in the chamber. The degree of mixing was difficult to ascertain quantitatively so therefore a smaller experiment was designed to qualitatively investigate the effect of baffle dimensions and positions (Figure 3-26).

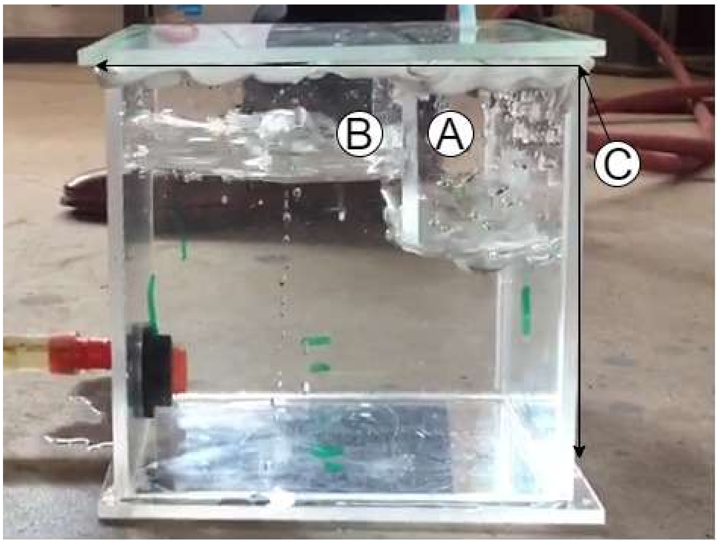

Figure 3-26: Model used to investigated different baffle arrangements

The pressure build-up in chamber A was simulated using a bicycle pump. Point C which is at the top right vertex was used as a reference point. Mixing was investigated with baffles positioned at a quarter and a third distance from point C, as well as baffle heights of half and three-quarter the height of the headspace from the top. It was observed that positioning the baffle at a quarter distance away from point C caused more disturbance in the fluid in chamber B. The two investigated heights did not have significant observable difference in disturbance caused in chamber B. Therefore, this led to the final design of the baffle on the prototype to be positioned similarly and with a height of half the headspace of the digester. This is expected to improve mixing whilst still maintaining a relatively smaller redundant gas headspace.

3.9.3. Temperature Control

A mesophilic temperature of 35˚C was chosen for the operation of the digesters. The initial plan to control the temperature of the digesters was through use of a solar panel connected to a battery, temperature controller (*Arduino microcontroller)*[13] and finally to a heater element and temperature sensor to be placed inside the digester (The proposed setup is shown in Figure 3-27)

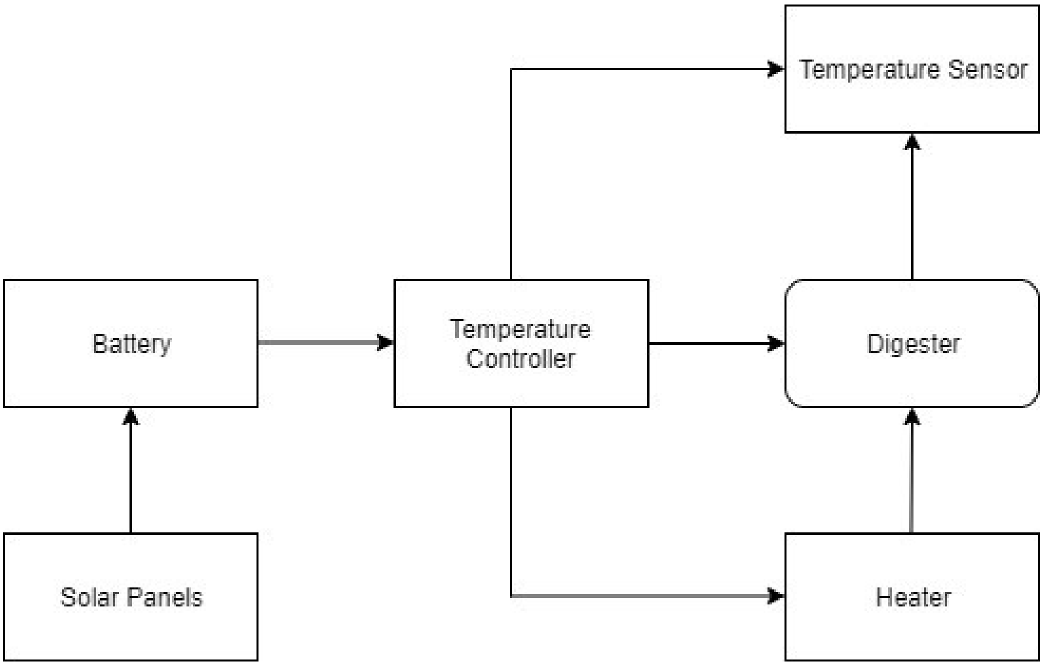

Figure 3-27: Proposed temperature control setup

This was not possible due to issues regarding obtaining the materials. Therefore, temperature control was achieved through use of an incubator shown in Figure 3-28 below.

[13] *Arduino* is an open source software and hardware company that designs microcontrollers. Detailed information about the subject can be found on https://www.arduino.cc/en/Guide/Introduction

Figure 3-28: Prototypes inside incubator

3.9.3.1. Gas Tightness Check

A common problem experienced by many anaerobic digester designers is making the digester airtight (Rosato, 2017). Indeed, such problems were experienced which required amendments. The gas tightness check of the digesters was performed as follows: 1) the digesters were filled up with water, 2) then a mark was placed on each day, 3) followed by close observation over a period of time (see Figure 3-29).

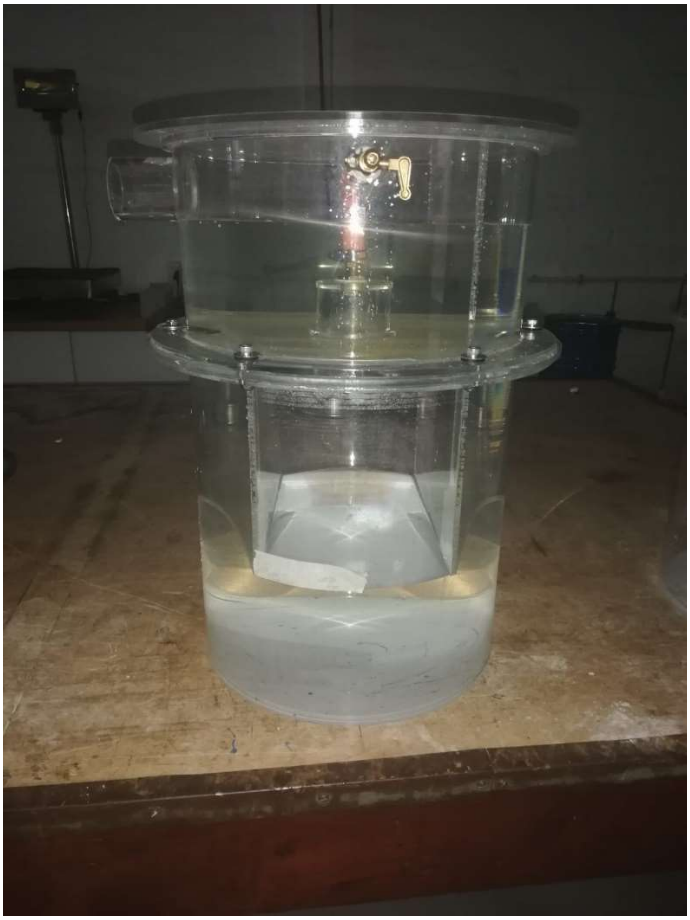

Figure 3-29: Digester prototype undergoing gas tightness check

3.9.3.2. Digester Start-Up Process

The digester was seeded with 75% Inoculum and 25% feedstock, therefore at an inoculum to substrate ratio of 4:1 which was observed by Liu et al. (2017b) as a suitable ratio to quickly start up a digester. The inoculum, which was also used during the BMP test, was collected from an active anaerobic digester at one of the households in the NLM area and immediately used for the start-up process. The feedstock was cow dung and it was collected from NLM and stored in a cold room at 4°C. Both digesters were purged with nitrogen gas and thereafter left to start-up for eight days. Gas analysis was performed until methane production was observed.

3.9.3.3. Digester Feeding Plan

The feeding of the digesters began on the ninth day after the start-up stage. The digesters were to be fed with cow dung. Cow dung was chosen as a feedstock because it has been shown to exhibit relatively better stability during the process of anaerobic digestion (Ibn Abubakar and Ismail, 2012). The aim of the experiment is to load the digesters at a relatively high OLR

The cow dung was to be fed at 15%TS at an OLR of 3.4kgVS/m^3/day at an HRT of 30 days. Microsoft excel was used to calculate the required amount of water and dung to be added to the digester each day. The amount of feedstock to be added to the digester at the required loading specifications was 550g.

3.9.3.4. Monitoring Plan

The amount of gas generated was measured each day using a GA5000 gas analyser. The analyser is able to record both volume (using flow rate) and quality of the gas. The gas volume was periodically verified using a liquid displacement mechanism as shown in Figure 3-30 and also using a metre rule. pH of the digester was periodically checked especially during the startup process. A summary of the digester specifications has been shown in Table 3-7.

Figure 3-30: Digester prototypes inside incubator during gas measurement

Table 3-7:Summary of digester prototype specifications

Parameter	Optimised	Control
Active Volume	21L	21L
Expansion Volume	10L	10L
Gas Storage Volume	9L	9L
Operating Temperature	35°C	35°C
HRT	30 Days	30 Days
OLR	3.4kgVS/m^3/day	3.4kgVS/m^3/day

3.10. Limitations Experienced during the Study

The study was conducted successfully despite limitations that were experienced. The limitations during the study have been summarised below:

3.10.1. Lack of Equipment

During the laboratory characterisation and BMP tests, some equipment was not available throughout the study. With respect to the characterisation tests, there was no equipment to test for pathogen indicators and the C/N ratio, therefore, samples were sent to external laboratories for testing.

The BMP test was associated with leaks that were rectified using waterproofing silicone. In addition, one of the tubes connected to the sample of human excreta was blocked and therefore, the analysis was done in duplicate which is still satisfactory according to Rosato (2017). However, accuracy could have been improved by performing the analysis in triplicate. The gas analyser was constantly available and therefore gas quality readings were limited.

3.10.2. Difficulty Obtaining some Information

During the "Rural Bio-Energy Project" at the five ECDCs, it was not possible to obtain certain information. This information includes: the daily quantity of human excreta and cow dung as well as design information about the septic tanks. Daily quantification of human excreta was not performed as it could pose a health risk to the ECDC personnel. The daily quantity of human excreta was estimated to be 85g per child according to Rose et al. (2015). Finally, it was not possible to measure the operational capacity at each ECDC and thus it was estimated through interviews and participatory observation.

4. RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results of the entire study which are analysed and discussed with respect to the aims and objectives. Information from the qualitative interviews that were conducted has been analysed first since it provided a basic starting point for many of the other investigations.

The presentation of the results begins with the NLM Rural Household Biogas Project Site Investigation and Troubleshooting. Issues identified within the sites were rectified using immediate solutions and devising long term solutions.

Characterisation test results were thereafter analysed to provide a basis for the BMP tests as well as the other interventions that were dependent on the feedstock. These interventions include; the design of the prototype, design of the anaerobic digestion process systems at the selected ECDCs as well as assessing the general quality of locally available feedstock at the NLM area.

The BMP data was used to assess the bio methane potential of the locally available feedstock in order to assess the most suitable feedstock for the rural households. Additionally, the BMP data was used to determine a feeding plan for the biogas interventions at the five ECDCs. The prototype was also designed based on the BMP data.

The designs at the five ECDCs have been presented and compared with the household biogas interventions to show how the systems were designed optimally using the results from the household biogas investigations.

Lastly the gas production of the optimised digester has been analysed with respect to the organic loading rate. The performance has been compared against a control.

All the results from each of the study sections were analysed and presented in the form of figures, tables and graphs. Additionally, discussion on each of the sets of results is presented. Raw data and other all other additional information has been presented under Appendix D.

4.2. Interviews

The interviews were conducted to extract the basic pieces of information required to carry out the entire investigation. The interviews also provided information on the social and economic perspective of the correspondents concerning use of the biogas technology in NLM. The complete interviews can be found in Appendix A with respect to the household interventions while the results from the interviews and participatory observation at the ECDCs have been covered in section 4.5.1. The results from the interviews are presented thematically as outlined under sub topics below.

4.2.1. Social Aspect

Biogas technology is a relatively new technology to the South African traditional setting. Correspondents at both households and the ECDCs generally provided positive social feedback about the technology. One household correspondent (Mrs.Ngcobo) expressed reservation on the process of generation of biogas. Mrs. Ngcobo indicated that some people expressed apprehension to the mere thought that biogas uses faeces or dung as a raw material for biogas production. This is an important social aspect that contributes to cultural social stigma and traditional taboo that could affect the adoption of this technology and could potentially affect the widespread promotion and adoption of the biogas technology.

On the other hand, the other two correspondents (Mrs. Zuma and Mrs. Mhlangeni) reported that they got positive feedback from friends and neighbours who expressed interest and readiness to adopt the technology. The two correspondents attributed the positive feedback to the energy because of financial and manpower time savings as a result of adopting the technology. Wide scale sensitisation would most likely convert the sceptical rural households to adopt the biogas technology.

However, to fully assess the social aspect of the biogas interventions, a larger sample number of interviewees need to be involved. A larger sample None the less, the limited households interviewed have given an overall idea on the social aspects of adopting biogas technology in rural South Africa.

4.2.2. Economic Aspect

All the correspondents provided positive feedback about the economic perspective of utilising biogas technology. All the correspondents praised the biogas technology with all of them happy that they have experienced significant financial savings from using biogas as a substitute to the paraffin and LPG that they had been buying. They also experienced savings in terms of man power time consumed collecting firewood which they had been using before.

The savings in time enabled them to perform other economic activities and all the correspondents were excited with adopting a cheaper energy source.

With respect to the ECDCs, an estimation of the monthly cost of energy (LPG) at each site was determined. According to managerial personnel at each ECDC, Ukuhlalanathi and Siyaqubekha, the largest (see section 4.5.1.) spent about R800 on 20 kg LPG cylinder refills twice a month while Vukuzenzele and Sphumele spent R400 on 20 kg LPG cylinder refills once a month. Babunene ECDC spent about R200 on 9kg LPG cylinder refills once a month. Based on the results shown in Table 7-2, Appendix B, it is estimated that biogas quantities can meet the cooking needs for the ECDCs, however, biogas quantities are based on BMP values. Controversies regarding BMP values were extensively discussed in section 3.8.5. which necessitate future monitoring of these biogas quantities. Moreover, the quantity of human excreta was not determined on site and instead estimated to be 85g per child according to Rose et al. (2015).

4.2.3. Technical Aspects

The correspondents interviewed all expressed happiness that organic household waste can be fed daily into the digesters. They noted that the option of feeding the digesters daily with domestic organic waste is a blessing in disguise and this has led to an improved household hygiene while at the same time generating biogas that is used as energy source however they reported insufficient knowledge about the technical aspect of the digesters. The interviewees however revealed insufficient knowledge about the technical aspects of the technology such a maintenance. Mrs. Ngcobo's piping had been clogged and she wasn't able to assess this until it was investigated and pointed out to her. The interviewees also revealed that all the household digesters were fed with greywater They also mentioned that the Khanyisa projects personnel instructed that no bleach and other strong detergents be added to the digester feed. This important technical information revealed the inputs of the household digestion process systems.

With respect to the ECDCs, interviews were used to evaluate each site and the information has been analysed in section 4.5.1. Additionally, all leadership capacity was qualitatively assessed using the interviews. The interviews also contributed to the site selection process for the ECDCs. Interviews at the ECDCs also provided estimations of the cooking hours spent at the ECDCs in order to assess their demand and supply of biogas. Furthermore, the principal energy source for cooking was determined to be LPG through these interviews.

4.3. (A) Maintenance and Troubleshooting at Rural Household Digestion Process Systems

Results suggests that the current design of bio-digester built by SANEDI in NLM is largely successful at producing viable gas with locally available feedstock, however persistent infrastructural issues related to the delivery of gas to the home, as well as a number of socio-cultural factors, have severely impacted the success of the interventions. The technology has been critically assessed, and thereafter, identified infrastructural issues have been presented with on site and long term solutions.

4.3.1. Analysis of the Rural Household Anaerobic Digester

The anaerobic digester typology used at the 26 rural households is the CFDD. Figures 4-1 and 4-2 show the original design drawings of the digesters used at the NLM households.

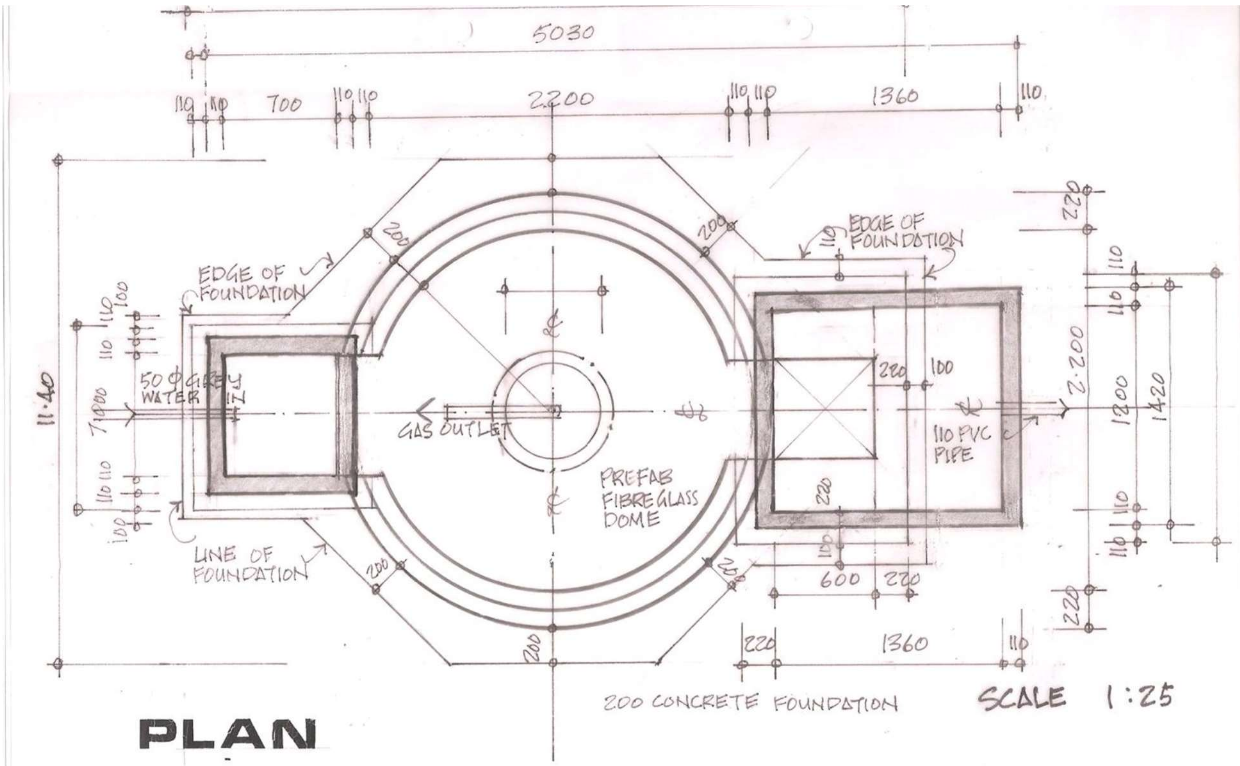

Figure 4-1:Original plan view drawing of digester (Khanyisa Projects, 2014)

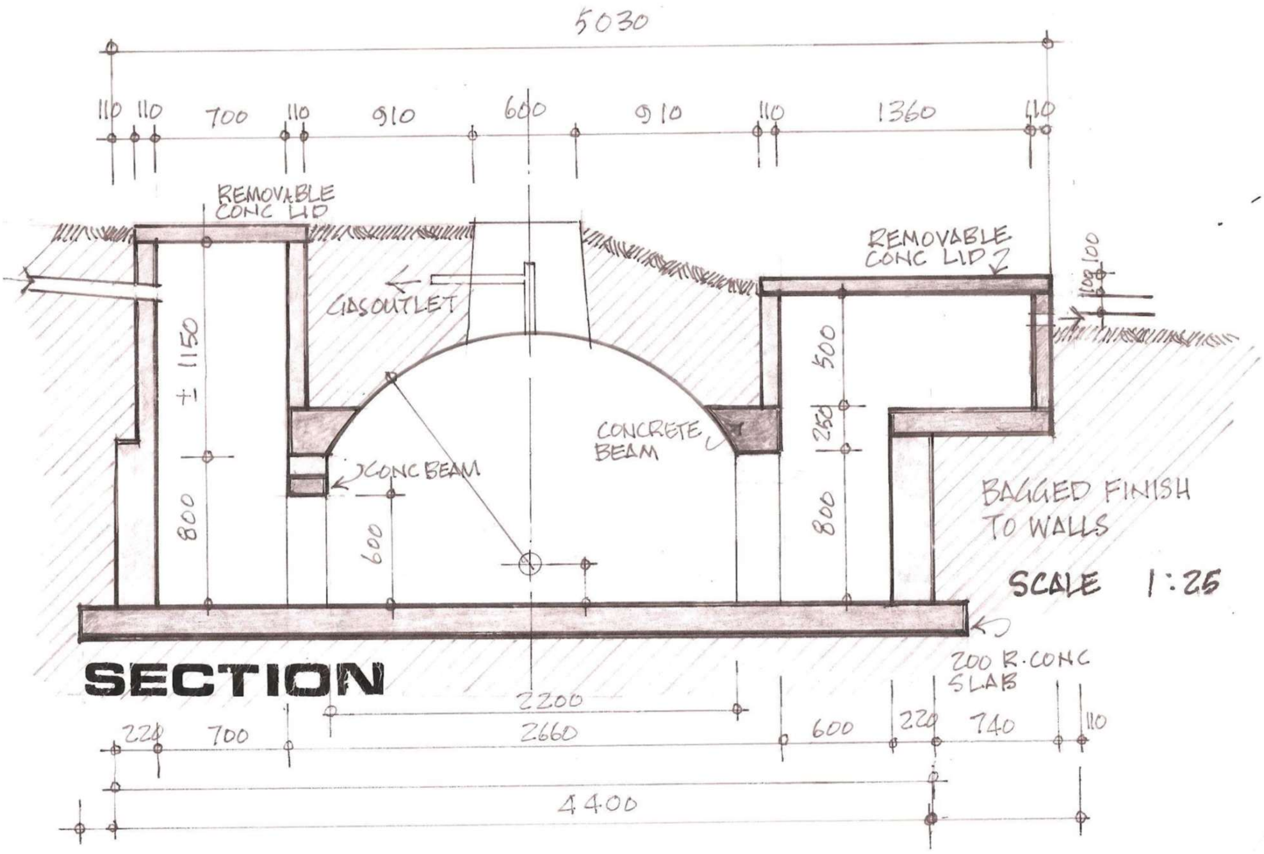

Figure 4-2: Original longitudinal section through digester (Khanyisa Projects, 2014)

Figures 4-1 and 4-2 were used to understand the parts and operation of the technology. The digester functions like any other Chinese dome digester whereby slurry, which enters through the inlet tank, is displaced by produced biogas in the dome into the expansion chamber. However, it is unique in that it has a fibre glass dome instead of a brick and mortar dome like in most CFDD designs. The cost of a digester's installation was estimated using the budget which was attained through Khanyisa Projects. It was calculated to be approximately R72,000. The original budget can be found in Table 7-4, Appendix C.

The anaerobic digester was found to have relatively long life span if designed and maintained correctly. Twenty of the 26 digesters were still operational since they were installed, and six were found not to be producing gas (see Table 4-2). The digester also created value to the people, not only through its purpose, but by creating employment and developing people's skills during its installation. Advantages and disadvantages of the digester technology in the context of the NLM households have been described in Table 4-1 below:

Table 4-1: Advantages and disadvantages of the rural household digester

Advantages	Disadvantages
Long life span if designed, constructed and maintained correctly	May be difficult to achieve airtightness
No rusting nor moving parts that require extra maintenance	Construction, materials and overall installation may be expensive
Good underground insulation	Installation requires skilled workers
Construction created employment	Non-user friendly inlet tank lids
Fibre-glass dome provides extra insulation and eases construction compared to a conventional brick and mortar dome	Difficult to reinstall dome if damage occurs
Expansion chamber provides pressure to the stored gas	Fibre-glass dome is expensive and may be difficult to fabricate
Employed workers that were trained gained skills	Overall costs of installation can be expensive
Construction materials are readily available	Not portable
Mixing of digester content occurs during gas extraction and production	Mixing may be limited

Table 4-2: Six non-operational household digesters with respect to each household

Beneficiary	Notes
Shandu	Building in which the stove was located was wrecked. Dome valve, all piping and the stove had been removed. Nobody was home at the time of the visit.
Hlongwa	The dome valve had been removed from the digester, all piping and the stove had been removed. Residents say the digester had not been operational for two years and that they no longer kept livestock.
J. Ngcobo	The dome valve was irreparably damaged and all piping as well as the stove had been removed. Residents say the digester had not been operational for many years.
Ngiba	The stove and all piping had been removed from the site. All valves and fittings had also been removed. The residents could not recall when the damage had occurred, but remembered that they had stopped feeding the digester in 2016.
Ndlovu	The stove and all piping had been removed from the site.

Of the six, four were not producing gas because of removed gas outlets at the dome (Figure 4-3).

Figure 4-3: Damage to dome gas outlet valve fitting

One of the household digester did not ever work due to cracks and one had a burnt dome due to a wild fire (Figure 4-4).

Figure 4-4: Digester dome burnt due to wild fire

It was not possible to salvage any of the digesters that had removed gas outlets because it would require one to enter inside the digesters, which were filled up with slurry, to install the outlet fitting. It is important to note that one of the households with an operational digester had been evacuated. The digester is now a waste product which emphasises its inherent disadvantage which is its inability to be uninstalled and reclaimed.

The digester with a burnt dome (Figure 4-4) was also unsalvageable on site because it was out of the scope of the project. The solution to the problem, however, would require emptying of the digester, purchase of fibreglass material, fabrication of a fibreglass dome and finally installation.

Lastly, the digester that had cracks was salvaged. The following methods were followed to repair the cracks inside the digester:

Step 1: An investigation was performed through consultation with personnel at Khanyisa Projects that were involved in the installation of the digester. Through these interviews it was established that the cracks in the digester were likely to be caused by settlement of the base slab.

Step 2: A basic structural analysis was performed on the digester to reveal the possible points of failure. Bending stresses on the digester were analysed. It was indeed found, as literature suggests, that the highest bending stresses occur at the vertices along the cross-section of the digester. Therefore, it was decided that these points would require plastering.

Step 3: The mortar mix that was used for plastering was exactly the same as the one that was used to construct the digester; however, to ensure air/water tightness, it was decided that a water proofing admixture would be added to the mortar mix.

Step 4: The mortar mix was prepared accordingly and was used to plaster all the points of weakness inside the digester.

Step 5: The plaster was left to set and the digester was later visited and filled up with water and left for two weeks and the levels of water were marked.

Step 6: The digester was visited and indeed the water held up to the same level and hence the digester was salvaged using basic structural engineering principles.

4.3.1.1. Conclusion to Critique of Existing Household CFDD.

Over the five-year period, twenty out of the 26 digesters were still producing gas and out of the six dysfunctional ones, one had a structural failures and one had a burnt dome. The other four anaerobic digesters were not functioning due to damaged or removed dome valves, which are difficult to repair or replace. This shows that if a CFDD is installed and maintained correctly, it will have a long life-span. To improve probability of airtightness, one should use a waterproofing admixture to the mortar mix used for its construction. Installation should also be done carefully to prevent settlement of the slab below the digester structure which causes leaks.

It can be concluded that the CFDD can be suitable for a rural setting especially if a prefabricated dome is used as it eases construction and reduce the risk of leaks at the dome. In addition, simplicity should always be maintained when designing digesters for rural areas to enable easy rectification where required. Education to users about maintenance can improve the success rate of these digester types.

Despite the advantages of the technology, the high cost of installation and long pay-back periods can be unfavourable for rural households which are associated with low income so the dissemination of rural household digesters is most feasible if sponsored. In addition, literature suggests that mixing in a CFDD may be limited, therefore agitation mechanism could improve the performance of the digester, however, parts that require maintenance should be avoided in a rural context. In addition, temperature can be increased and maintained within these digesters using solar energy.

4.3.2. Analysis of The Infrastructural Components of the Household Anaerobic Digestion Process Systems

The infrastructural components of the biogas system were identified and evaluated with respect to each household. Many of the problems were recurring at the households. One out of the 26 households had a functioning anaerobic digestion process system with sound infrastructure as well as an operational digester. A full analysis at each household can be found in Table 7-5, Appendix C. Identified issues and their causes have been summarised in Table 4-3 together with the on-site solutions that were devised as well as possible sustainable methods to mitigate the identified issues.

Table 4-3: Troubleshooting at NLM households

Problem	Reason	Current Mitigation Method	Sustainable Mitigation Methods
Leaks in gas line	Pipelines were cut mistakenly by residents as they were digging the land	Fixed using fittings	•Pipeline protection using sleeves •Pipeline marking •Using more durable piping material
Broken taps on valves	Taps on valves were made of plastic which is susceptible to damage	Taps were replaced with metallic taps	Use of metallic taps rather than plastic
Blocked Stoves due to rust	•The stoves were made of cast iron which is susceptible to rust •Rusting is catalysed by H_2S and condensed water in the biogas	Drill was used to unblock holes in stoves	•Stoves can be replaced with more rust-resistant types that are made of material such as stainless steel or ceramic which is rust proof. •Installation of H_2S and water traps
Gas leaks in stove	Rust	Silicone was used to block leaks	Same as above
Faulty stove manifolds and valves	Rust	Manifolds and gas valves were replaced	Same as above
Condensed water in gas line	•No water traps •Inconsistency in pipeline slope	Tee washing machine valves were used to remove condensed water	•Use of water traps •Install gas pipeline with consistent downward slope towards the digester
Non-user-friendly holding tank lids	•Lids are too heavy for some of the elderly and young residents •Many lids were found broken because they are made of precast concrete	N/A	Use of plastic holding tank lids
H_2S gas	No H_2S removal mechanism	N/A	Use of H_2S gas scrubbers
Unsanitary disposal of digestate	No digestate disposal mechanism	N/A	Use of a soakaway or reed bed

The scope of work for the “SANEDI Refurbishment project” allowed for only maintenance but six of the 26 households were chosen for implementation of the sustainable solutions to the identified issues. These households are a representation of an optimised household biogas system in the context of the NLM “SANEDI Refurbishment project”, however, the recommendations can be used for infrastructural optimisation of household biogas systems in South Africa. The household biogas systems were designed as shown in Figure 4-5. This represents an optimised household anaerobic digestion process system.

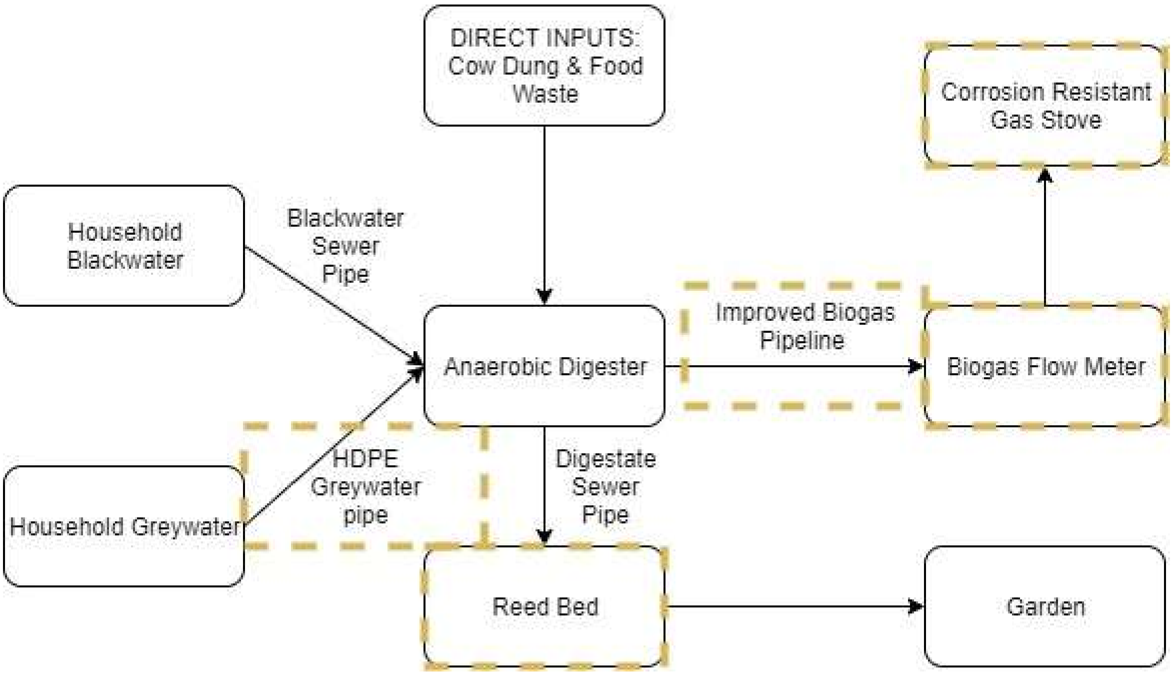

Figure 4-5: Optimised household digestion process system flow chart

The optimised biogas system was designed with respect to the following key points:

- Gas pipelines were installed with downward slope to prevent condensed water from getting trapped in gas pipelines. In addition, a new robust type of gasline pipe (see Figure 4-6) was used instead of the previously used PVC pipes as shown in figure. This pipe is made up of a longitudinal butt welded aluminium layer that is surrounded on the inside and outside by layers of cross-linked polyethylene. The inner and outer PEX layers inhibit scaling and corrosion while the aluminium provides it with strength which suits the users at NLM. Furthermore, this new type of pipe is easier to install and cheaper than the previously used PVC pipe.

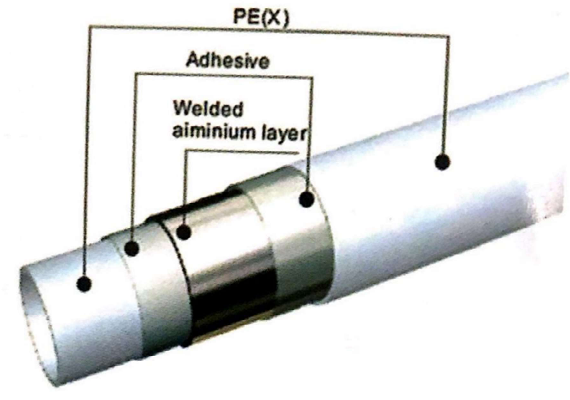

Figure 4-6:New improved gas conveyance pipe

- A best attempt was made to obtain a ceramic burner stove but it was not possible to obtain one within the project timeline. Therefore, a stainless steel stove with a less rust susceptible burner was installed.
- The H_2S concentrations in the biogas that was tested on site was of a concentration that could be harmful, however, the smell is also used to identify gas leaks, so therefore, in this rural context, hydrogen scrubbers should be considered to mitigate H_2S pollution.
- The digester holding tank lids were replaced with lightweight, cheap polymer lids. These are easier to move and still durable.
- All toilets within the households will be connected to the digester, if possible, to provide a sanitation service. Additionally, soakaways will be installed at each household to enable a sanitary disposal of the digestate.
- A flow meter was added to enable monitoring of available gas quantities. However, this may not be a mandatory additional component unless feedstock is limited.
- Lastly, the greywater pipes that were used previously were made of LDPE and were prone to damage from farm tools as shown in Figure 4-7. Therefore, HDPE pipes were used because they are stronger and were actually cheaper in cost.

Figure 4-7: Damaged LDPE greywater pipe(left) and new robust HDPE pipe(right) to be installed

4.3.2.1. Conclusion to Critique of Household Anaerobic Digestion Process System Infrastructural Components

Infrastructure within biogas systems is important for success of biogas provision in rural South Africa. Results show that despite having operational anaerobic digesters at 20 out of the 26 households, only one of the households had an operational biogas system with sound infrastructure.

Long term methods have been described to prevent infrastructural issues sustainably. These methods can be utilised for small scale anaerobic digestion process systems in rural South Africa

4.4. Feedstock Investigation

4.4.1. Quantification of Feedstock

The quantity of human excreta was estimated using the average faecal mass generated by a typical student at an ECDC, 85 grams, and stool frequency of 1 (Rose et al., 2015). This was then multiplied by the average attendance of the day at each ECDC. The results yielded an average faecal mass of 12kgs, 3kgs,2kgs, 5kgs and 9kgs at Ukuhlananthi, Vukuzenzele, Babunene, Sphumelele and SiyaQhubheka. The average quantity of food waste generated was found to be 5kg at the Ukuhlalanathi ECDC and was taken as representative. The daily food waste quantification over sixty-four days is shown in Table 7-1, Appendix B. The daily food waste quantities at each ECDC were 3kgs, 1kg, 0.5kg, 1.2kg and 2.5kg at Ukuhlananthi, Vukuzenzele, Babunene, Sphumelele and SiyaQhubheka. It was not possible to quantify the amount of cow dung available but, at least two cows, were visually identified around each site. This data was used to devise a feeding regimen for the systems at the ECDCs.

4.4.2. Characterisation Test Results

The characterisation tests revealed crucial information about the substrates that were investigated. It provided an idea of their biodegradability and other characteristics that may aid in understanding their behaviour with respect to the process of anaerobic digestion. This information was used to optimise the process of anaerobic digestion at the respective sites. Optimisation enabled recommendations for feeding regimens, digestate disposal and operational conditions. The results from the characterisation tests, before the BMP test, with respect to each substrate that was tested have been shown in Table 4-4.

The concentration of pathogen indicator organisms was also investigated to assess the pathogen reduction during anaerobic digestion as well as to assess the extent of pollution in the digestate that was obtained from the field.

Table 4-4:Characterisation results of respective substrates

Sample	TS(%)	VS(%)	BOD (mg/l)	RI7 (mgO_2/gDM)	COD (mg/l)	C/N	VFA/TA	Pathogens (CFU/g-Solids) or (CFU/mg-Liquids)			
								E.Coli	***Faecal Coliforms***	***Faecal Streptococci***	***Enterococci***
CD (Solid)	25.23 (±0.11)	88.03 (±1.03)	N/A	246.41 (±10.98)	35,916 (±3091.61)	30.86:1	N/A	16,600	N/A	1100	6,000
FW (Solid)	23.93 (±0.32)	95.46 (±0.43)	N/A	175.62 (±12.67)	100,921 (±9052.21)	26.48:1	0.8	<10	N/A	92,000	149,000
HE (Solid)	8.47 (±0.69)	83.07 (±0.41)	N/A	704.34 (±21.04)	95,867 (±8632.21)	5.88:1	N/A	21,600	N/A	130,000	250,000
DG1 (Liquid)	1.56 (±0.78)	26.33 (±0.56)	607.33 (±54.69)	N/A	18,724 (±1523.21)	14.26:1	N/A	2,000,000	2,000,000	12,000	150
DG2 (Liquid)	5.60 (±1.60)	36.39 (±0.40)	1798.33 (±167.17)	N/A	18,670 (±1453.32)	N/A	N/A	27,000	180,000	180,000	220
IN (Liquid)	3.26 (±0.11)	74.77 (±0.86)	311.67 (±21.57)	N/A	21,640 (±1856.32)	12.40:1	N/A	3,600,000	18,000,000	10,000	110

4.4.2.1. Cow Dung (CD)

CD exhibited the highest solids content. As mentioned earlier (Ciborowski, 2001), cow dung with greater than 10%TS requires dilution before anaerobic digestion to enable optimal performance of the digester. The characterisation results show that CD is rich in biodegradable matter. Evidence of this can be seen by the relatively high VS content and RI7 value. However, cow dung is associated with high fibre content (up to 50%) which makes it slightly less biodegradable. Therefore, despite its high biodegradability, it may be slower to breakdown due to the fibre content.

Sawyerr et al. (2019) and various other authors have found the C:N ratio of CD to fall within a suitable range (18:1 to 30:1) similar to the value of 30.86:1 that was obtained. This ratio would promote a suitable environment for microbes to digest cow dung. Furthermore, Theresia and Priadi (2017) has reported the ideal buffering capacity of cow dung; this enables cow dung to be stable during the process of anaerobic digestion.

4.4.2.2. Food Waste (FW)

FW had the highest COD and second highest VS and RI7 values. The sample of food waste that was investigated contained portions of maize mill, white rice, meat and beans but predominantly maize mill which mainly contributed to the solids content. Soup was also present within the food waste which contributed to the liquid content. Maize mill and white rice are polysaccharides but are not complex in nature compared to carbohydrates found in for example brown rice (Panawala, 2017).

The C/N ratio of FW was found to be in the ideal range. This could be attributed to the presence of both carbohydrates rich (maize mill and rice) and proteinaceous substrates. Despite the ideal C/N value, food waste is known be associated with issues related to insufficient alkalinity. This issue was experience during the start of the BMP test whereby the food waste went sour. Therefore, to digest food waste, one must be cognisant of the VFA/TA ratio. The VFA/TA ratio was found to be 0.8 which is beyond the ideal range. The ratio had to be brought down using sodium bicarbonate to provide sufficient alkalinity during the anaerobic digestion process.

4.4.2.3. Human Excreta (HE)

HE demonstrated a low solids content compared to values obtained by various authors such as Rose et al. (2015). This could have been due to the sample collection. In addition, observation of the sample shows that it contained a high urine content. Despite the low solids content, the sample had a high volatile solids content which shows that it contains a high quantity of biodegradable matter which is supported by its high biochemical oxygen demand shown by the RI7 result. Biodegradable matter in human excreta includes: 25–54% bacterial biomass (Feachem, 1978), 2–25% protein matter (Stephen and Cummings, 1980), 25% carbohydrate (Wierdsma et al., 2011) or any other undigested plant material and, 2–15% lipids (Rose et al., 2015).

HE had the lowest C/N ratio of all the samples tested. The C/N ratio of human excreta is known to be low due to the high nitrogen content predominantly contributed by urine. Faecal nitrogen is present in the form of nucleic acids, undigested dietary protein as well as bacterial protein and shed intestinal mucosal cells (Canfield et al., 1963). Such a low C/N ratio may pose risks of ammonia toxicity, however authors such as Song et al. (2011) have reported successful anaerobic digestion of human excreta.

HE exhibited the highest concentrations of all three pathogen indicator organisms. This was expected as human waste is known to contain a number of disease causing organisms. For this reason, unsanitary disposal of human excreta can lead to the spread of a number of diseases as shown by various studies (Gerardi and Zimmerman, 2005).

4.4.2.4. Field Digestate (DG1; DG2)

As mentioned earlier, the digestate produced by the digesters at the households in NLM is disposed of onto the adjacent land. There are no soakaways nor sanitary effluent disposal mechanisms put in place at any of the households. This poses the risk of pollution due to pathogens as well as the high oxygen demand associated with such waste.

As mentioned earlier, anaerobic digestion can be efficient at pathogen reduction. Despite the digestion undergone by these substrates, both DG1 and DG2 exhibited high pathogen pollutant concentrations. The COD and pathogen indicator concentrations for both DG1 and DG2 are beyond disposal limits prescribed by the National Water Act and Water Research Commission (2009). Uncontrolled disposal of such effluents could disturb the course of natural process inside the soil. In addition, with time, this could also lead to groundwater pollution coupled with the pathogen contamination. In addition, it is important to note the high concentration of faecal coliforms in DG1. This is caused by the human excreta that is fed to the digester DG1 was sampled from. This raises concerns about digestate that accrues from human excreta fed digesters. Indeed, such high pollutant concentrations necessitate the safe disposal of digestate. Digestate can be disposed of in a sanitary manner using a soakaway or a reedbed which enables water reuse for irrigation.

4.4.3. BMP Test Results

The BMP test was concluded after 30 days of testing. Subsequently, the contents of each bottle were then re-characterised and the results are shown in Table 4-5.

Table 4-5: Characterisation Test after BMP Test

Sample	**TS(%)**	**VS(%)**	**BOD (mg/l)**	**COD (mg/l)**	**pH**	**Pathogens (CFU/g-Solids) or (CFU/mg-Liquids)**			
						E.Coli	***Faecal Coliforms***	***Faecal Streptococci***	***Entercocci***
CD (Solid)	4.97 (±0.49)	76.80 (±0.15)	124.00 (±2.65)	9,036 (±772.32)	7.12	20	N/A	<10	<10
FW (Solid)	3.31 (±0.22)	52.35 (±0.45)	204.00 (±3.61)	42,126 (±4333.32)	6.80	<10	N/A	<10	<10
HE (Solid)	8.47 (±0.75)	70.07 (±0.52)	114.67 (±8.62)	27,809 (±2123.32)	8.26	40	N/A	40	80
IN (Liquid)	2.08 (±0.10)	65.07 (±0.59)	105.03 (±2.65)	2,258 (±196.35)	7.00	N/A	N/A	N/A	N/A

A considerable reduction in all parameters after the BMP test can be observed. This is expected during the process of anaerobic digestion. The COD removal efficiencies[14] for the CD, HE and FW samples were 76%, 71% and 58% respectively. This can be expected as anaerobic digestion breaks down organic matter. CD had the highest COD removal efficiency, followed closely by HE; this can be attributed to the fact that both samples are already in the process of degradation and may already contain some acclimatised anaerobic microorganisms. This is because HE and CD are both derived from animal guts which contain anaerobic microorganisms.

In addition, there was a significant removal of pathogens, up to 99%, from all the samples, including HE, which showed the highest initial concentrations of all pathogens as shown in Table 4-4 earlier. The significant removal of both pollutants (COD and pathogens) during the BMP test supports the use of anaerobic digesters within sanitation systems. However, despite this, other factors may cause the persistence of pathogens within anaerobic digestate. This can be shown by the high concentrations exhibited by the samples obtained from the field whose results were presented earlier in Table. These factors could include an interruption in the HRT caused by higher loading resulting in an incomplete digestion. Therefore, it can be proven that anaerobic digestion significantly reduces pathogens but anaerobic digestate still requires safe disposal.

The graphs of the cumulative volume against the time are shown in Figures 4-8, 4-9 and 4-10 for CD, FW and HE respectively. The daily gas production for each sample against time has been shown in Table 7-9, Appendix E. The maximum methane concentrations obtained by CD, FW and HE were 55%, 60% and 61%.

[14] Pollutant Removal Efficiency $= \frac{Concentration\ Before - Concentration\ After}{Concentration\ Before} x 100\%$ Peavy HS, Rowe DR and Tchobanoglous G (1985) *Environmental Engineering.* Singapore: McGraw-Hill International Editions.

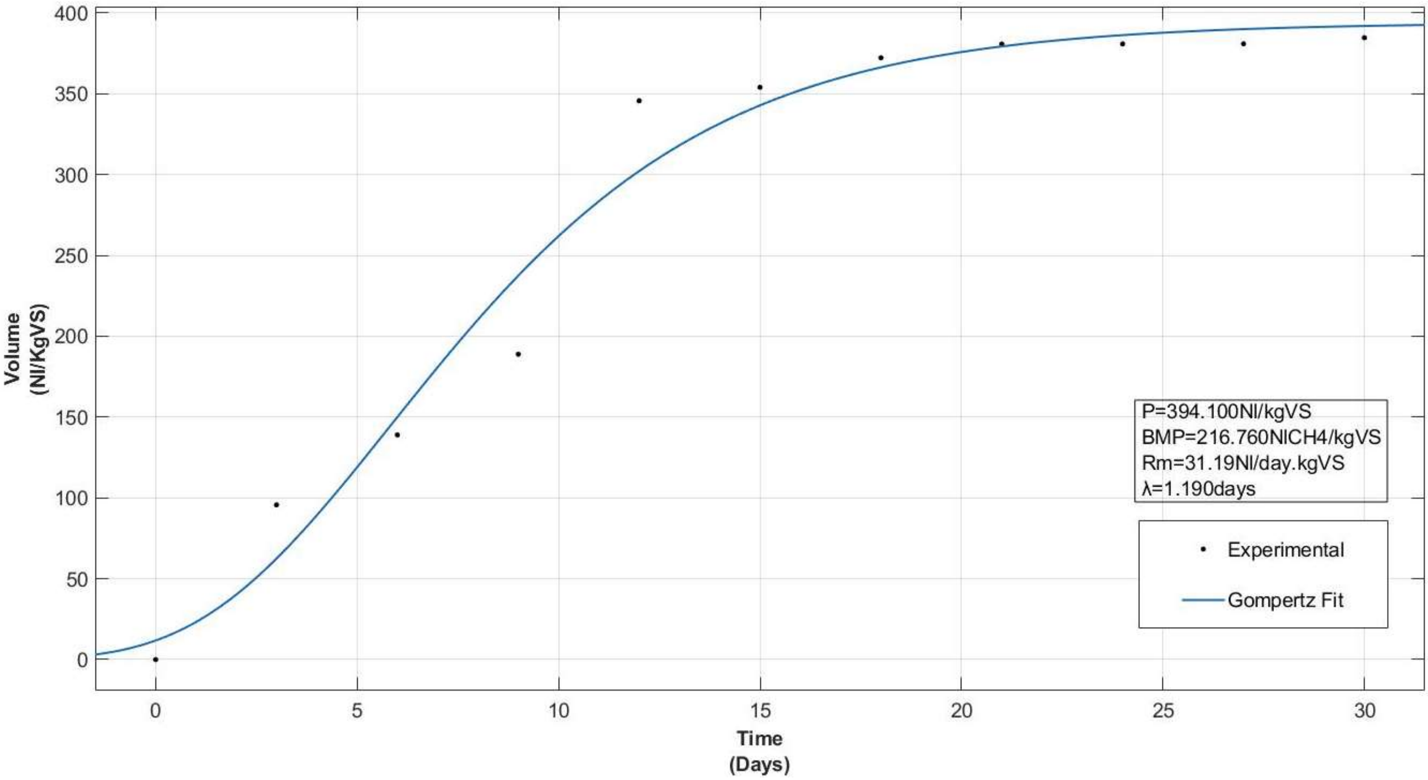

Figure 4-8: Cow Dung (CD) cumulative biogas volume against time

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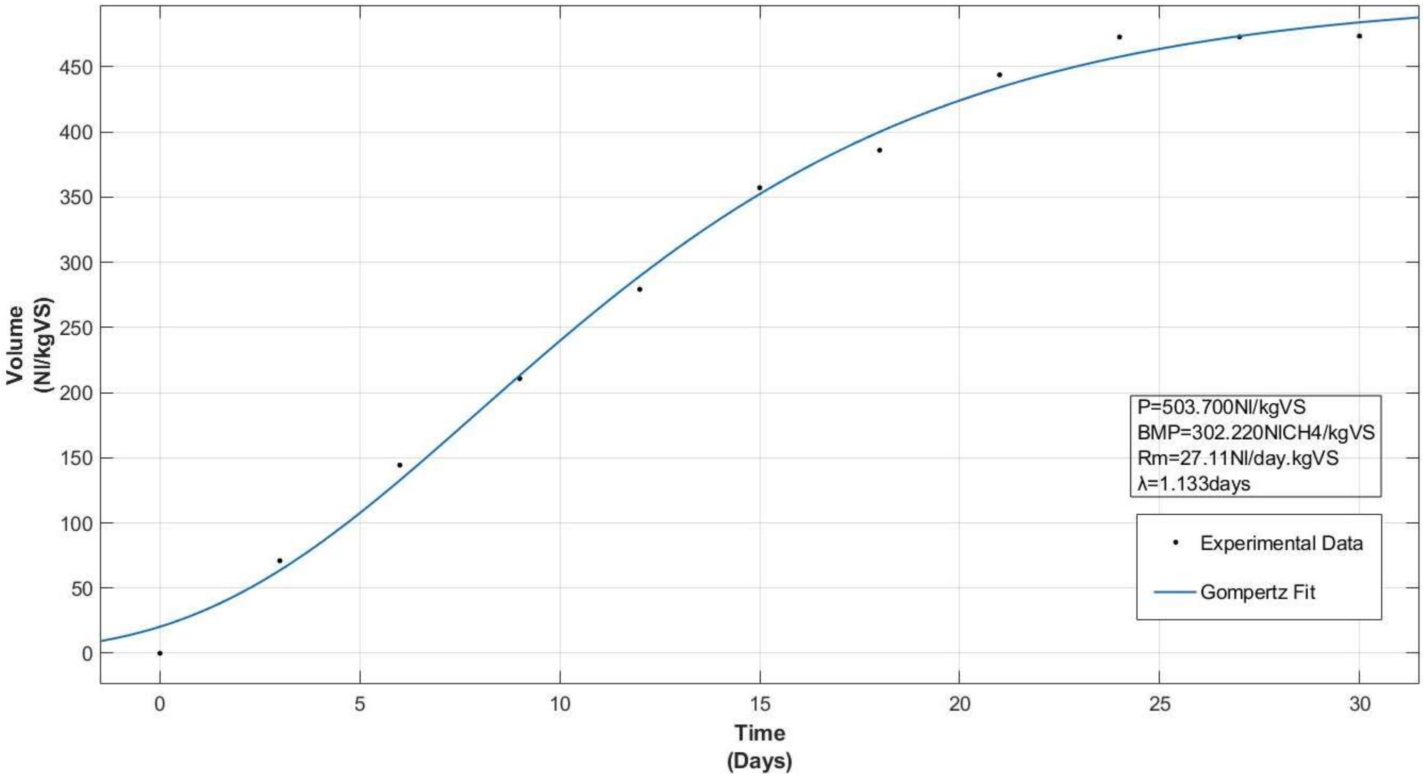

Figure 4-9: Food Waste (FW) cumulative biogas volume against time

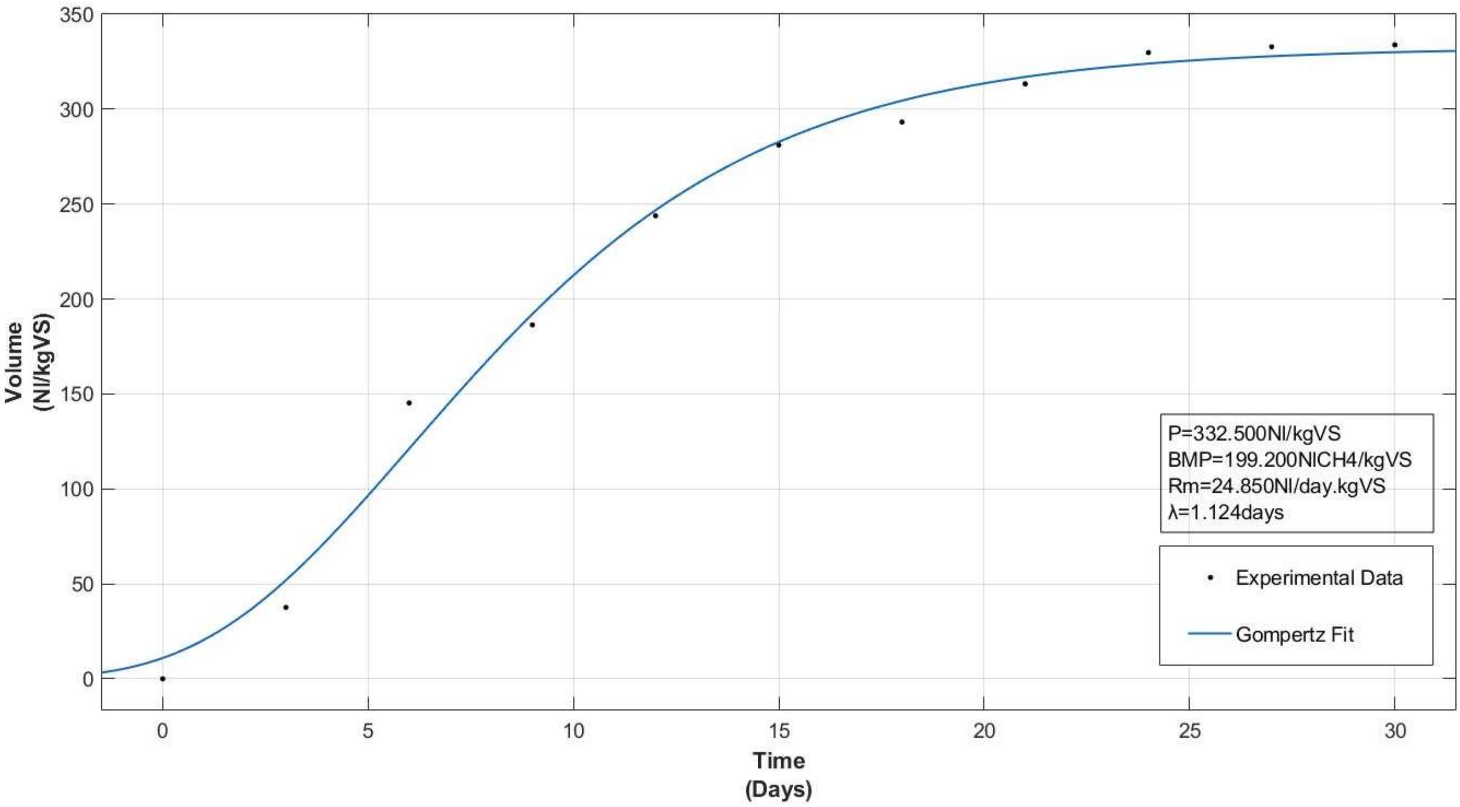

Figure 4-10: Human Excreta (HE) cumulative biogas volume against time

All the samples that were tested exhibited short lag phases and similar gas production rates (R_m). This can be attributed to the quality of inoculum that was used. All the substrates underwent grinding during their preparation resulting in smaller particle size which in turn allowed more surface area for microbes to digest. Smaller particle size within a substrate also supports a quicker hydrolysis stage. Hydrolysis, as mentioned earlier, is the rate determining stage and therefore, the quicker it occurs, the faster the rate of the degradation will be. The BMP values obtained fall within the ranges of various authors shown in Table 3-5 earlier. However, none of the BMP values matched those in Table 3-5 exactly which is expected due to the great variability in samples, inoculum and operational conditions.

FW yielded the highest biogas quantity and BMP. As mentioned earlier, the FW sample consisted of predominantly maize mill which is calorie dense carbohydrate. According to Rosato (2017), maize mill is an easily degradable substrate that leads to high BMP. However, the sample had low content of proteinaceous waste and hence had low alkalinity. Substrates that contain low alkalinity will go “sour” if the latter is not manually added. This is an issue that was experienced during the BMP test, as mentioned earlier. It is difficult to compare BMP values of food waste because of the great variability in samples (Fisgativa et al., 2016).

CD had the highest production rate (R_m) and the second highest biogas yield and BMP. A high production rate can be expected from cow dung because of its suitable C/N ratio, as explained earlier. In addition, CD already contains a significant population of methanogens; this could explain the fast production rate despite CD’s fibrous nature. CD also contains sufficient alkalinity for the process as shown in a study by Castro et al. (2017). CD has indeed been reported by several authors to be a suitable feedstock for anaerobic digestion (Ibn Abubakar and Ismail, 2012; Castro et al., 2017; Hasan et al., 2018), as mentioned earlier.

HE had the lowest biogas yield and BMP. The sample that was tested contained urine which is associated with high ammonia content. In addition, human excreta had a low C/N ratio which supports this suspicion. Therefore, the low BMP may be as a result of inhibition by ammonia which can also be supported by its pH value of 8.26. Human excreta has been reported to be a suitable feedstock by Mang (2010) however, faecal quantities may not be sufficient in most cases especially at household level. Therefore, domestic biogas digesters fed with human excreta may require supplementation.

4.4.4. Conclusion to Feedstock Investigation

The characterisation tests revealed crucial information about the way substrates may behave during anaerobic digestion. The results show that anaerobic digestion can be utilised within a sanitation system but concerns may arise regarding the safe disposal of digestate.

Furthermore, the results show that food waste is capable of yielding high quantities of methane, however, it may be difficult to control its VFA/TA ratio. Cow dung is the most suitable substrate, compared to food waste and human excreta. Cow dung yields significant quantities of methane and does not require any alteration to enable smooth anaerobic digestion unlike food waste (due to acidity) and sometimes, human excreta (due to ammonia toxicity). Co-digestion of these substrates must be considered to maximise the value of different types of feedstock for example; food waste and human excreta can be co-digested and the excreta provide the alkalinity required for methane production from high energy food waste. However, careful consideration should be make to the feeding ratios with specific focus on the C/N ratio amongst other factors.

4.5. (B) Anaerobic Digestion Process System Implementation at Five ECDCs in NLM

The optimised anaerobic digestion process systems at each of the five ECDCs have been shown using layout drawings in Figures 4-11 through to 4-15. These layout drawings will guide the overall subsequent sections that follow which entail the process of optimisation of these systems. All components and systems described are shown within the drawings for each ECDC.

Figure 4-11: Ukuhlalanathi ECDC site layout drawing

Figure 4-12: Siyaqhubeka ECDC site layout drawing

Figure 4-13: Vukuzenzele ECDC site layout drawing

Figure 4-14: Sphumelele ECDC site layout drawing

Figure 4-15: Babunene ECDC site layout drawing

4.5.1. Site Selection

The site selection process was facilitated by the ward counsellors at NLM. Eight possible sites were visited and investigated according to the selected criteria as shown in Table 4-6. Management capability was assessed from poor through fair to good and was qualitatively investigated using available staff and through interviews. The rest of the parameters were obtained through interviews and physical confirmation.

Table 4-6: Preliminary qualitative investigation at the ECDCs

Name of Possible Site	Number of Users	Source of Water	Type of Toilets	Presence Of Garden	Onsite Kitchen	Available Feedstock	Management Capability
Kethokuhle	23 Children 3 Staff	None	Pit Latrine	No	No	-Human Excreta -Food Waste -Chicken droppings	Poor
Sqalokuhle	28 Children 4 Staff	None	Pit Latrine	No	Yes	-Human Excreta -Food Waste	Poor
Zamani	28 Children 2 Staff	Municipal Truck	None	No	No	Food Waste	Poor
Siyaqhubeka ✓	103 Children 7 Staff	Municipal Truck that fills rainwater tanks	Pit Toilets	Yes	Yes	-Cow Dung -Human Excreta -Food Waste	Good
Babunene ✓	20 Children 4 Staff	Water tank refilled by truck	Pit Latrine	Yes	Yes	-Cow Dung -Human Excreta -Food Waste	Poor

Sphumelele ✓	52 Children 5 Staff	Neighbouring Yard Tap, Rainwater Tank	Pit Latrine	Yes	Yes	-Human Excreta -Food Waste -Cow Dung	Fair
Vukuzenzele ✓	39 Children 6 Staff	Yard Tap	Water Closet	Yes	Yes	-Human Excreta -Food Waste -Cow Dung	Good
Ukuhlalanathi ✓	134 Children 9 Staff	Yard Tap Rainwater Tank	Pit Toilets	Yes	Yes	-Human Excreta -Food Waste -Cow Dung	Good

(continued)

Out of the eight sites that was investigated, five of them were selected and they include; Sphumelele, Vukuzenzele, Babunene, Ukuhlananathi and Siyaqhubeka ECDCs. Five sites were selected as per the project requirements as well as the aforementioned criteria.

Human excreta was the principal feedstock for the bio-digesters at all the ECDCs along with food waste and cow dung from nearby sources. The available feedstock was used to calculate the amount of biogas that could be attained with respect to each site (this aspect is dealt with in detail in section 4.5.6.). The interviews revealed enthusiasm by the ECDC personnel to use the digesters to manage their own household food waste, and were keen to advise the pupils to do the same. This would provide a food waste management method for them.

4.5.2. Process System Design

After a comprehensive assessment of the flow chart prescribed in Figure 3-5 earlier, a new process flow chart was designed with respect to the selected sites which is shown in Figure 4-16 below. This flow chart represents the optimised anaerobic digestion process system for the five ECDCs which functions as both an organic waste (food waste and cow, in this context) management and a sanitation system.

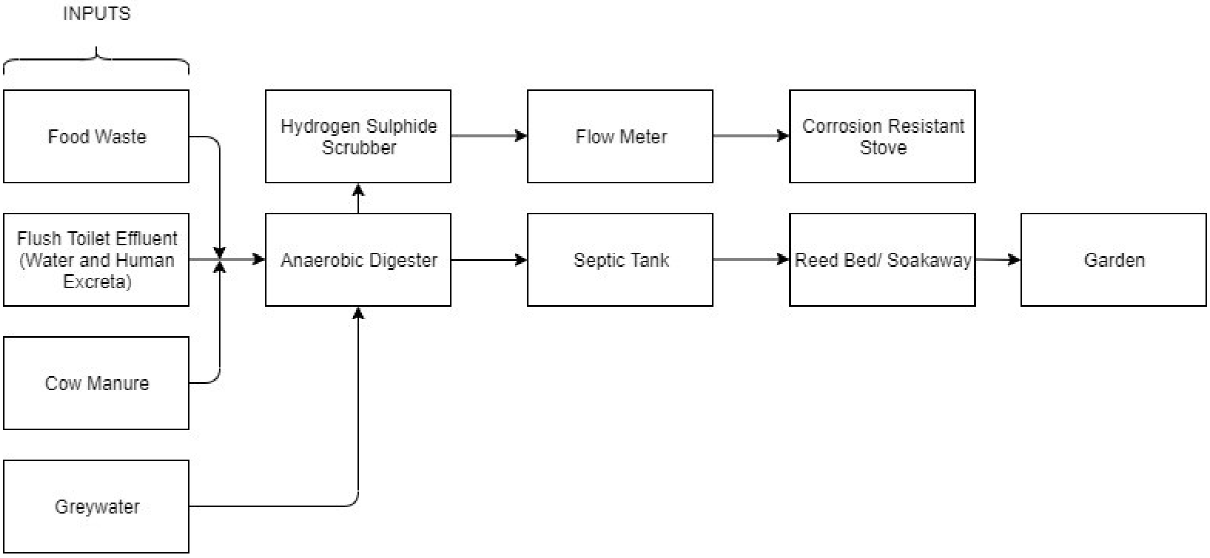

Figure 4-16: Optimised anaerobic digestion process system flow chart for ECDCs

4.5.2.1. Inputs

The food waste feedstock will enter into the digester directly without shredding and maceration. This was done to eliminate the risk of failures that would require maintenance and furthermore, the predicted amount of food waste (see section 4.5.6) was not so high to necessitate the process. However, a rudimentary method using a bucket and a stick was recommended to the users to reduce the particle size which is critical especially during hydrolysis.

An important input for the optimal operation of, both the toilet and anaerobic digester, was a reliable source of water. In addition, it was important for the water to reach the toilet system for flushing as well as handwashing after toilet use. Only Vukuzenzele ECDC had such a source of water. Therefore, at the rest of the sites, rainwater tanks that were engineered to provide reliable supply (see section 4.7.3.3.) were installed.

4.5.2.2. Anaerobic Digester Process Design

A single stage anaerobic digester (see section 4.7.3.1.) was selected for the process due to two main reasons. Firstly, it was not possible to obtain a supplier of a two stage domestic bio-digester; hence designing a two stage system would be expensive and pose difficulties in achieving airtightness. Secondly, a two stage digester was not deemed necessary based on the nature of the feedstock. A two stage digester is usually used for feedstock associated with low buffering capacity for example food waste. Cow dung and human excreta can provide enough buffering capacity to prevent the digester from going sour.

In order to achieve heating requirements, the digester would be installed underground. About a metre below ground level, temperature tend to remain fairly constant which is important for methanogenic bacteria. Though, higher temperature could be achieved on hotter days above ground, the day and night temperature fluctuations would inhibit the bacteria. The use of solar energy for heating would be expensive and introduce more complexity to the system that could pose issues associated with maintenance which is not ideal in a rural context.

4.5.2.3. Septic Tank

At three of the selected sites, there were septic tanks present on site (Figure 4-17). The effluent from the digester was designed to run through these septic tanks. Septic tanks treat human excreta using predominantly anaerobic bacteria but also both using aerobic and anoxic bacteria depending on the depth in the septic tank (see Figure 4-18).

Figure 4-17: Septic tanks at Vukuzenzele(Top), Siyaqhubeka (Left) and Ukuhlalanathi(Right)

Figure 4-18 below describes the formation of aerobic, anoxic and anaerobic zones within cell clusters. This provides an idea of how the zones would occur with respect to depth within the septic tanks.

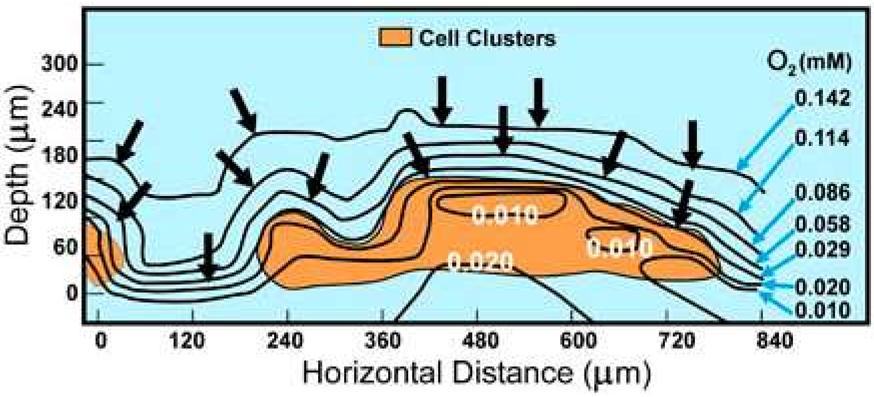

Figure 4-18:Oxygen content within cell cluster with respect to depth (Kaplan, 2010)

Therefore, effluent from the digester can undergo further treatment to reduce the COD and BOD. A septic tank has been reported to have a COD removal of about 50% (Dan and Dan, 2013). Therefore, a septic tank will further reduce COD in the digester's effluent and also further reduce pathogens similarly to a digester. Aerobic treatment following anaerobic treatment also enables the conversion of ammonia to nitrites which get converted to nitrates and finally, anaerobic bacteria at the bottom can convert those nitrates into nitrogen thereby reducing the nitrogenous oxygen demand. Figure 4-19 describes aerobic and anaerobic decomposition as well as the results of the breakdown of carbohydrates, fats and proteins. It shows that aerobic processes can further degrade some of the final stabilised products of anaerobic processes

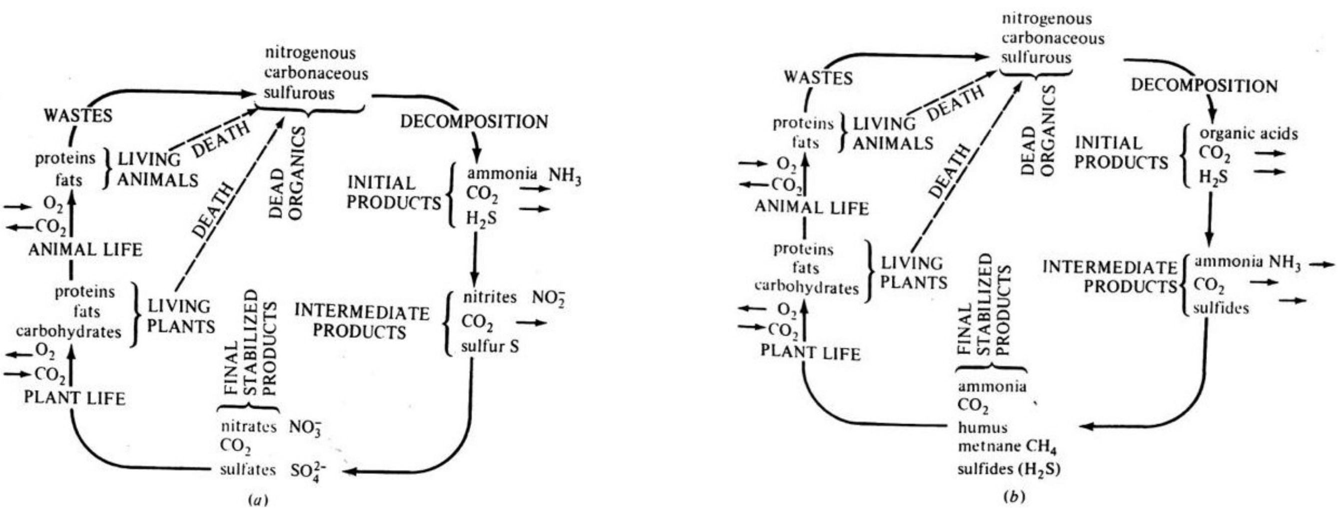

Figure 4-19: Metabolic processes- aerobic(left) and anaerobic (right) (Peavy et al., 1985).

In addition, further digestion in the septic tank will further reduce the pathogen concentration in the effluent. The septic tanks were therefore modified as shown in Figure 4-20. The tanks were provided with an inlet and outlet pipe at correct levels with respect to the entire system.

In addition, an access cover was added to the septic tanks as well as a vent pipe, where necessary as some of the septic tanks had these components missing. The vent pipe will encourage aerobic conditions in the tanks which will improve aerobic treatment.

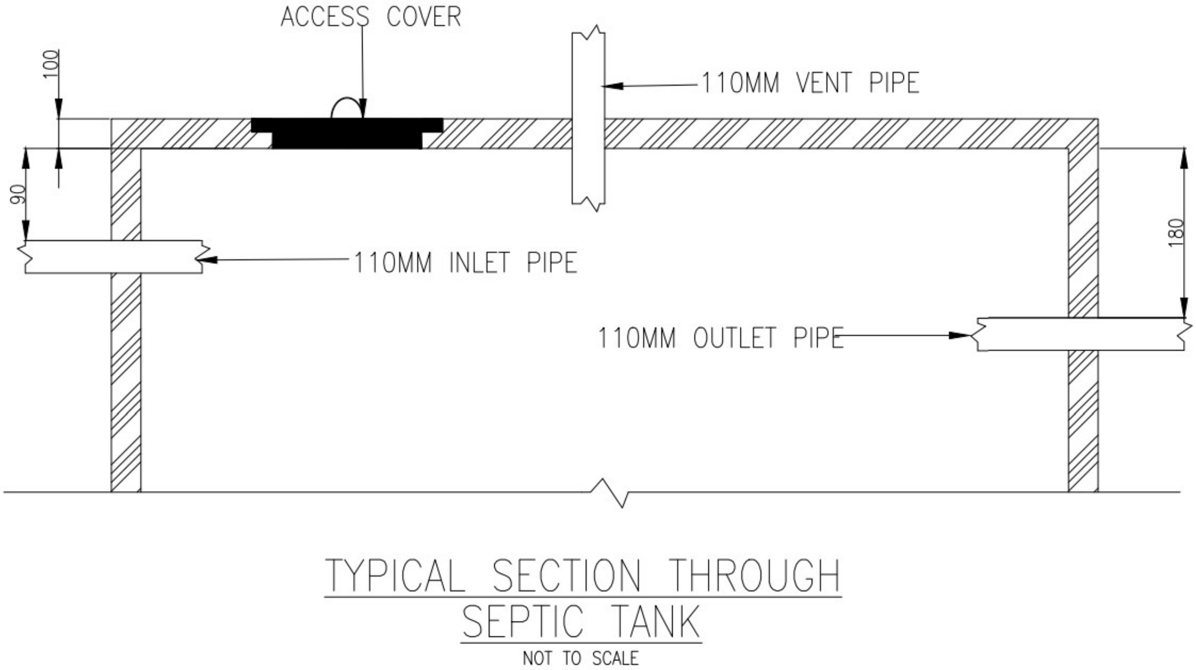

Figure 4-20:Typical section through modified septic tank

4.5.2.4. Disposal Process (Soakaway/Reedbed to Garden)

Following the septic tanks would be a soakaway or a reed bed. A soakaway is constructed one metre below ground level in order to take advantage of the aerobic zone which occurs at this depth below ground. The filtration gravel media will also facilitate further pathogen reduction. This would provide further aerobic treatment and enable safe disposal of the effluent through percolation into the adjacent gardens. The effluent would provide nutrients to the gardens. It is important to note that the soakaways were designed and installed using recycled tyre wrapped in a geo-synthetic material. It is an example of adding value to a waste product (waste tyres) and it reduces costs. The soakaway was only utilised at one of the sites (Sphumelele) and banana trees would be planted around the soakaway; this was done because of the type of garden present and would enable comparison of the two treatment processes. Reedbeds were designed and used at the 4 other sites because of their suitability (food gardens were in close proximity). The advantage of using reedbeds is that they release the effluent at a depth reachable by food crops. The design of both disposal methods has been shown in Figures 4-21 and 4-22 below

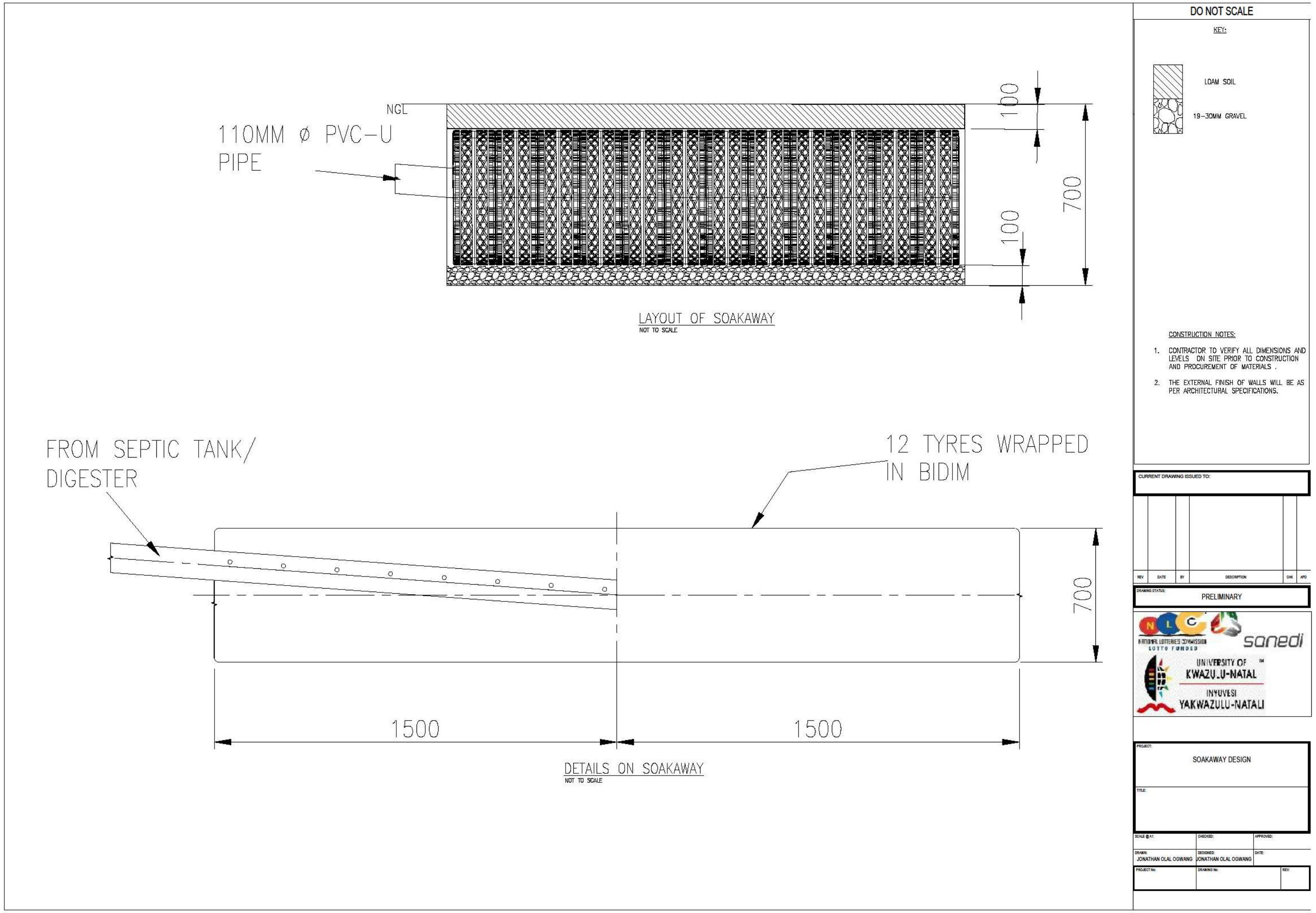

Figure 4-21: Soakaway Design

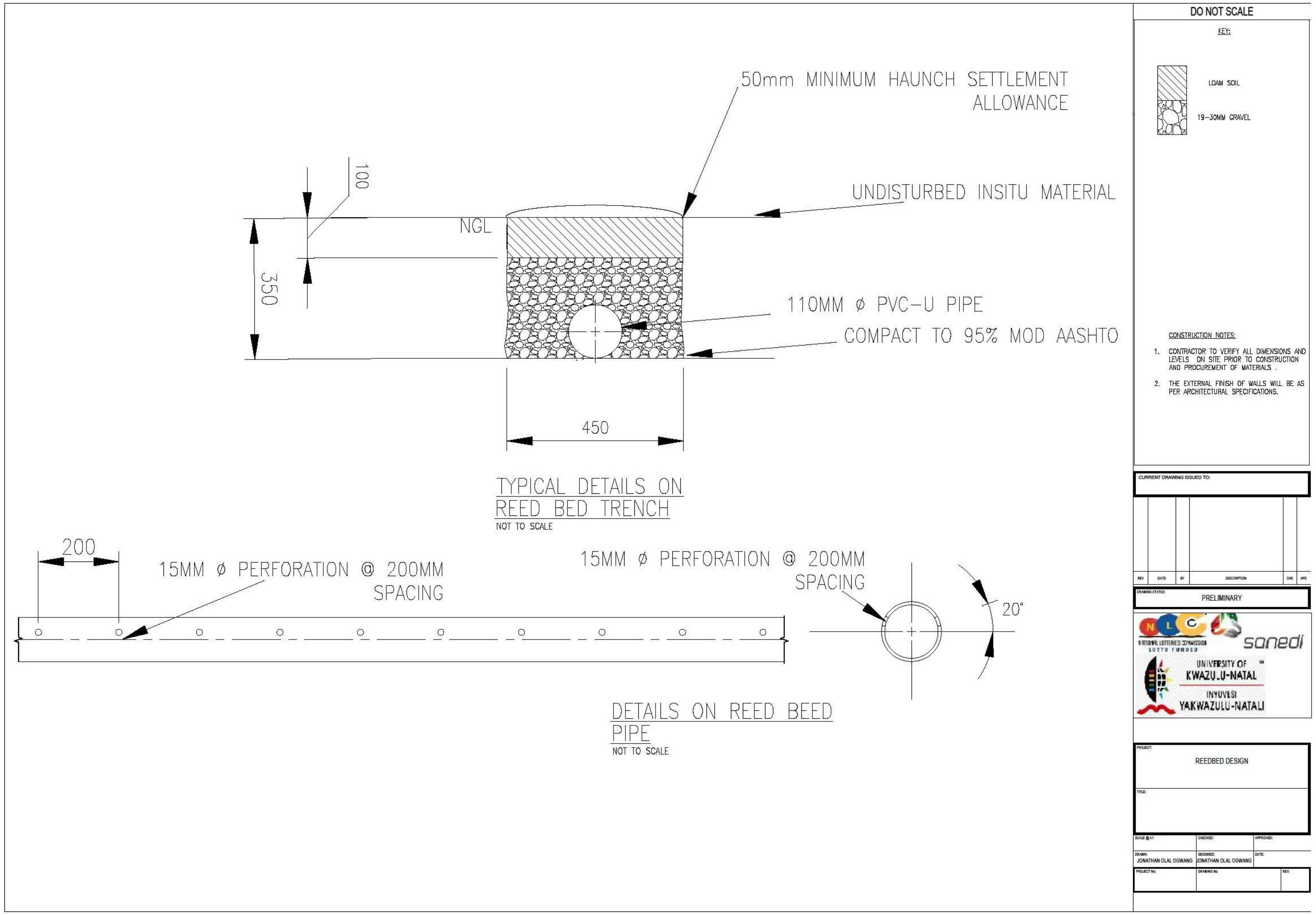

Figure 4-22: Reed Bed Design

4.5.2.5. Gas Scrubbing and Flow measurement

The biogas generated would be passed through a H_2S scrubber. H_2S is toxic to human beings and furthermore, the Agency for Toxic Substances and Disease Registry (2014) found that concentrations of H_2S greater than 50ppm will be detrimental to the health of children. All field visits to the household digesters revealed concentrations of higher than 50ppm as shown by the highlighted values (140ppm, 164ppm and 149ppm) in Figure 4-23 below.

Figure 4-23: Field biogas readings from household digesters in NLM

Children exposed to similar H_2S concentrations as adults can inhale higher doses because of their greater body weight to lung surface area ratios as well as increased weight to volumes ratios. In addition, they may be exposed to higher concentrations than adults in the same location due to their short stature and the higher H_2S concentrations found closer to the ground. Furthermore, children can be more vulnerable to corrosive gases than adults due to their relatively smaller airway diameter (Agency for Toxic Substances and Disease Registry, 2014). Therefore, it was necessary to install H_2S scrubbers.

In addition, it is important to know the quantity of gas available within the system, therefore, flow meters were to installed onto the system. Figure 4-24 shows an example of the setup of a H_2S scrubber and flow meter.

Figure 4-24:Example setup of H_2S scrubber and flow meter

4.5.3. Optimisation of System Components

The system designed for the ECDCs comprised of technical components that had to be carefully selected. These components to be selected include: the anaerobic digester, toilets, gaslines, pipelines, to mention but a few. Optimisations done during the "SANEDI Refurbishment project" have been applied to this project.

4.5.3.1. The Anaerobic Digester

Considerations were made to design and implement an optimised anaerobic digester however this was hindered by the timeline of the project. The most suitable anaerobic digester for the sites had to meet the following criteria:

- Long Lifespan: A long lifespan is governed by the structural integrity of the digester. Structural integrity is governed by the type of section and material used to design the digester. Therefore, the structural integrity of the available digesters was critically evaluated as part of the selection criteria for the most suitable digester.
- Relatively easy installation: The project was restricted by a specific timeline and therefore it was important to select a digester that would be easily installed in the shortest possible time.
- Very simple to operate and maintain: The intended users of the biogas had no experience with anaerobic digesters. Evidence of this is shown by the associated failures in the biogas systems used by the rural households. Therefore, it was important to select a digester that would be simple to operate and maintain.
- Must be able to be installed underground: The selected digester had to be installed underground in order to maximise the insulative nature of the ground since no additional heating would be considered. As mentioned earlier, additional heating

requires technology which would require additional maintenance and yet one of the goals to be met was little or no maintenance requirements.

- Optimal performance: Lastly, the selected digester would need to perform optimally and remain stable with respect to the feedstock available.

Therefore, after a careful review of the available domestic digester designs in South Africa, the “AGAMA BiogasPro” 6m^3 (ABP6) digester (see Figure 4-25) was selected for all the ECDCs. Despite the small population size at “Babunene” ECDC, a 6m^3 digester was still selected for the site due to inability to obtain a suitable smaller sized digester. The digester was selected as it best met the required criteria.

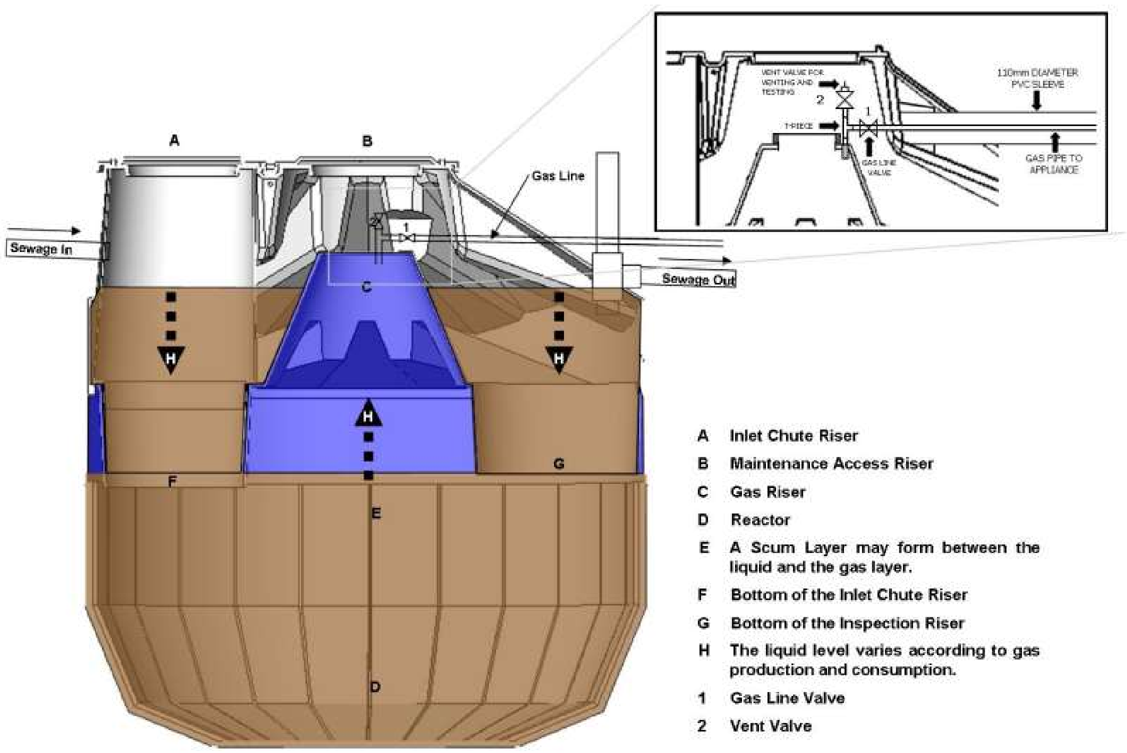

Figure 4-25: Vertical cross-section through ABP6 (Ayres, 2016)

The AGBP6 is a 6m^3 digester with a self-contained gas storage chamber of about 2m^3 as well as a 2m^3 expansion volume. It is a prefabricated digester which does not require construction and therefore can be easily installed and has a lower risk of cracks provided it is handled carefully. It is designed with its expansion chamber at the top of the digester; this enables pressure provision to the generated biogas. The digester structure is made of LLDPE which has been deliberately overdesigned with extra thick wall thickness. The ribbed structure enables it to better withstand ground forces as the load is reduced across the surface area of the structure. Therefore, it is expected to have a long lifespan.

In terms of performance, the digester is expected to be more stable because of the following reasons:

(i) The digester has good retention ability due to its completely vertical design. Some solids will settle to the bottom where the organic content will be digested and eventually flow out of the digester; inorganic matter will be more likely to settle at the bottom and will require removal, however, after a significantly long period. The design also reduces washout of methanogenic bacteria.

(ii) The digester's inlet sewer pipe will be attached to a "T-fitting" with a pipe that extends to the bottom of the digester (Figure 4-26). This reduces "short circuiting" by influent sewage. It will also reduce odours due to human excreta as one opens the inlet to feed the digester.

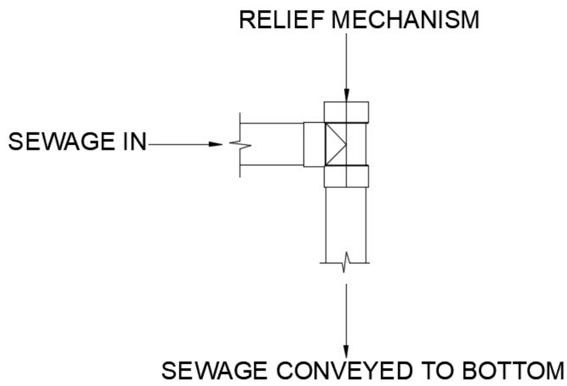

Figure 4-26:T-piece at AGBP6 sewage inlet pipe

The "AGAMA" 6m^3 digester was priced at R32,500 and offered at a 15% discount. A bio-bag digester was priced lower, however, it was deemed unsuitable for the site due to its susceptibility to damage, especially at an ECDC.:

Lastly the ABP6 does not have any moving or rusting parts and therefore will require low maintenance. A full description of the ABP6 can be found on the product data sheet shown in Figures 7-2 and 7-3, Appendix B.

4.5.3.2. Toilet System

A user interface is the way by which a user accesses a sanitation system (Tilley et al., 2014). The toilet system acts as a user interface as well as source of, feedstock (human excreta), and water (flush water). In most cases, the choice of user interface, in this case the toilet, is dependent on the availability of water. It is important to note that storm water and greywater do not originate from the user interface but can be treated along with the products of the user interface (Tilley et al., 2014). Toilets systems can be either dry or wet systems which differ in that the latter require water for operation. In the case of the systems at the ECDCs that required toilets, a wet system was necessary due to an anaerobic digester’s water requirements. Only one of the ECDCs (Vukuzenzele) had a wet toilet system (Figure 4-27) and therefore it was left intact and connected to the rest of the system.

Figure 4-27: Water closet toilet systems at Vukuzenzele ECDC

A pour flush toilet and a water closet are the two types of wet toilet systems available in South Africa. The main difference between a pour flush and a water closet user interface is the difference in water usage (a pour flush toilet uses 2 litres of water per flush while a water closet uses between 5 to 9 litres) (South African Council for Scientific Industrial Research et al., 2000). The anaerobic digesters will receive greywater as well as flush water but too much water in a digester will negatively affect its performance. Too much flush water over dilutes human excreta which may affect it optimal digestion (Colón et al., 2015). Therefore, in order to promote optimal performance of the digester and to conserve water, a pour flush toilet was selected to be used at the ECDCs where it was required. The pour flush toilet was supplied by “Envirosan” and is shown in Figure 4-28 below.

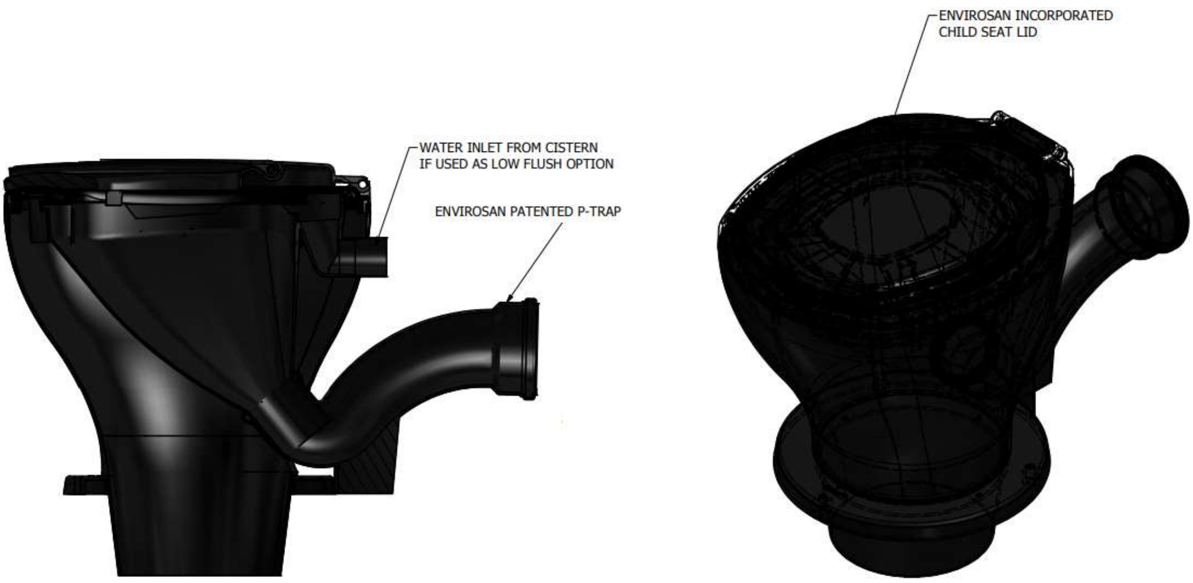

Figure 4-28: "Envirosan" pour flush toilet design, side view(left)& isometric view(right)

4.5.3.2.1. Toilet Structure

The toilets required a structure to provide shelter to the users. Therefore, a structural design was performed with respect to the toilets which is shown in Figure 4-30 and 4-31, overleaf. The structure was designed for the toilet structure at Ukuhlalanathi ECDC. Prefabricated structures were used for the rest of the ECDCs due to budget constraints (Figure 4-29 below).

Figure 4-29: Prefabricated toilet structure

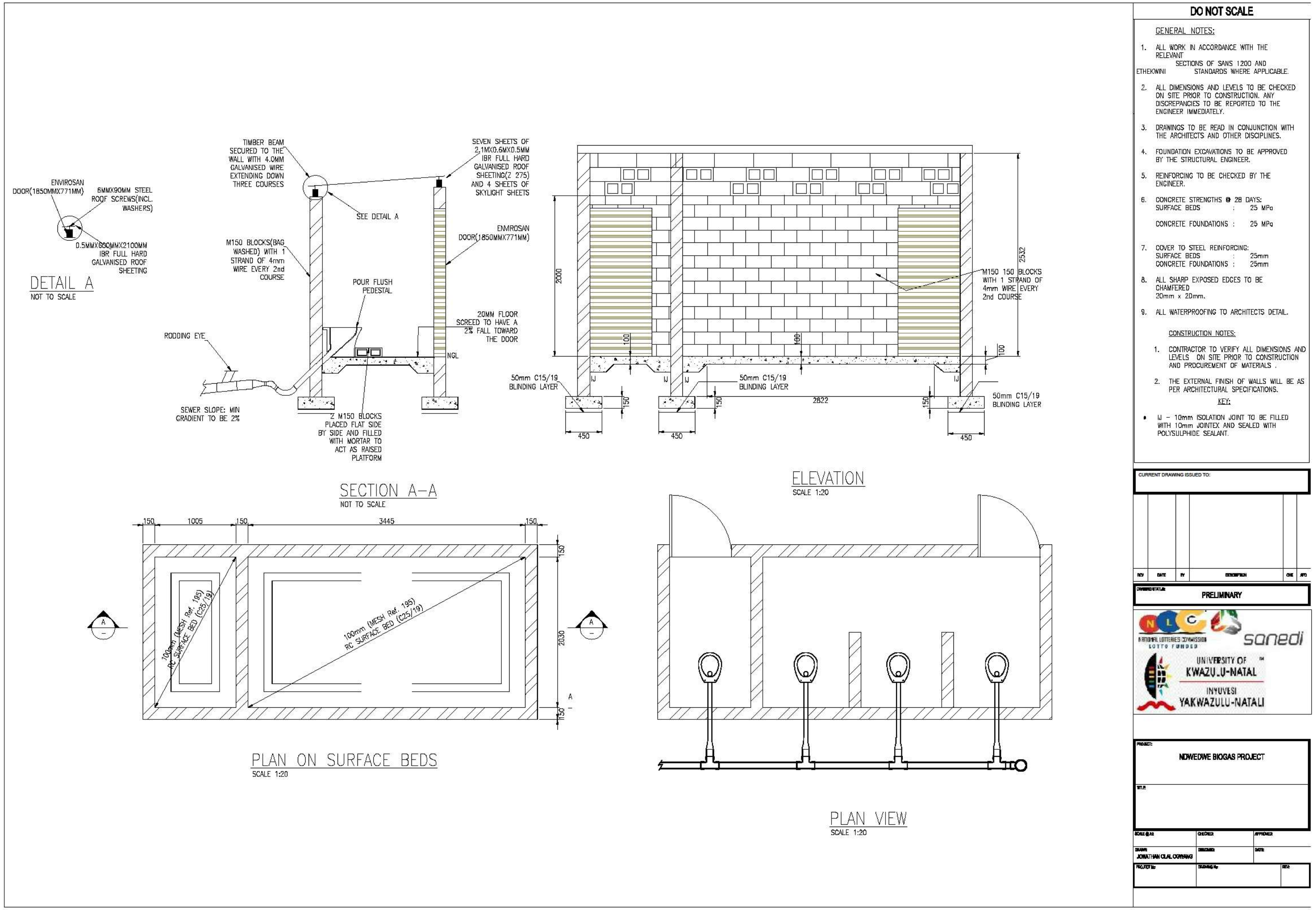

Figure 4-30: Design of toilet structure

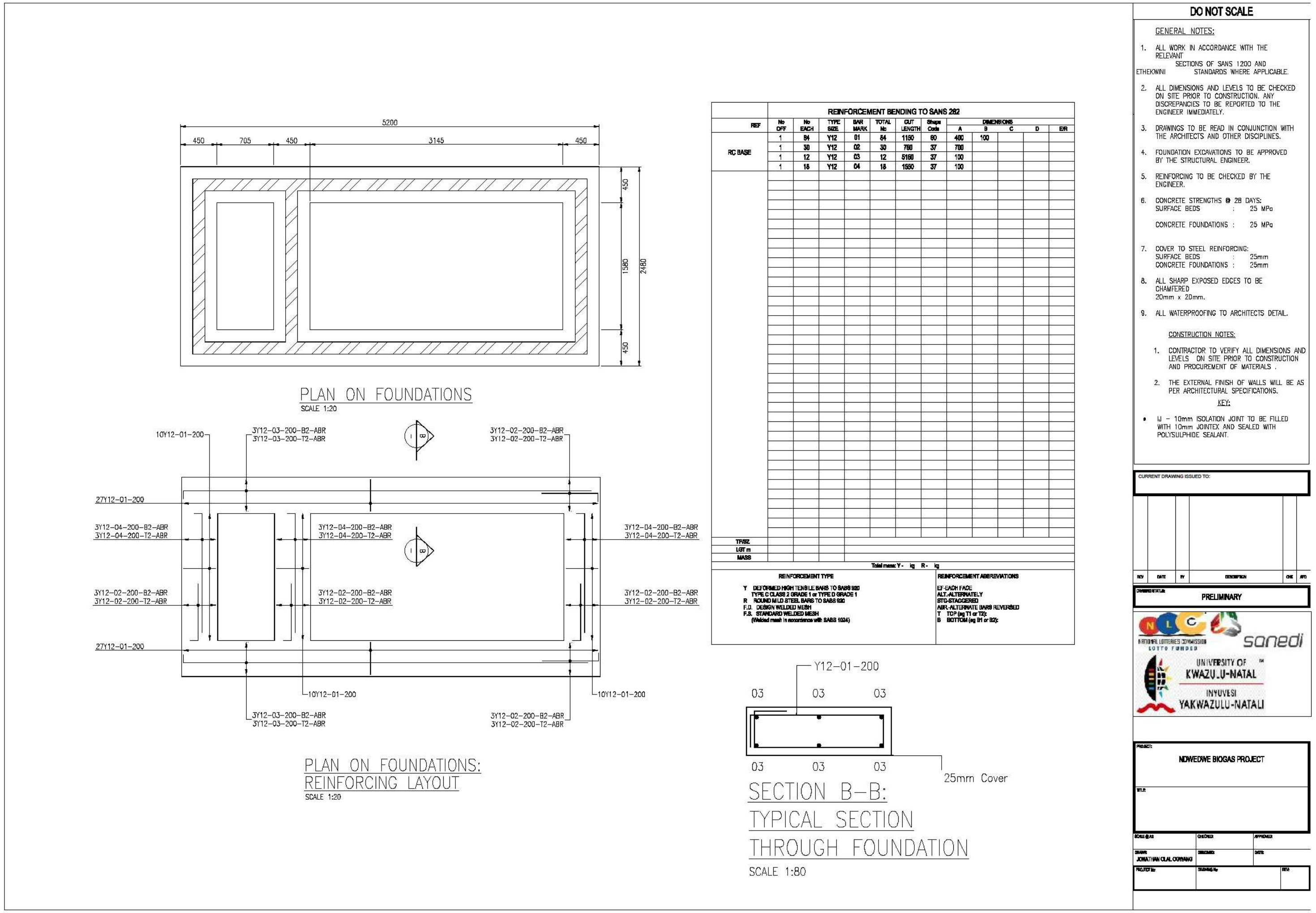

Figure 4-31: Reinforcement details of toilet structure

4.5.3.3. Ancillary Components

The ancillary components, in content, refer to the water supply components, gas, greywater and sewer pipes as well as the gas stove. Optimisation to the ancillary components of the entire system were performed. These optimisations were similar to the interventions made during the "SANEDI Refurbishment Project" with the aim of durability, improved performance and reduction in cost. Therefore, similarly, the improved pipe shown earlier in Figure 4-4 was used and in addition, the pipeline was installed with gentle downward slope towards the digester to prevent the problem of condensed water within the pipe during the system operation. The HDPE pipe and gas stove mentioned earlier with respect to the "SANEDI Refurbishment Project" will be used within the system as well. Lastly, ceramic burner stoves will be used which are corrosion proof.

4.5.4. Water Supply

An imperative component to the overall system was a water supply system to the toilets and hence the digester system. Rainwater tanks were present at each of the sites that required water supply interventions however they were not at favourable proximity to the toilet systems (see Figure). Therefore, additional rainwater tanks were installed and were linked using robust HDPE pipe. The tanks were linked such that they were able to fill simultaneously with the already present rainwater tanks. Already present water tanks were supplied with water from a yard tap or a municipal truck as mentioned earlier. The water supply system design has been shown in Figures 4-32 and 4-33, below, in detail, and has been illustrated with respect to each site in section 4.7.4. below.

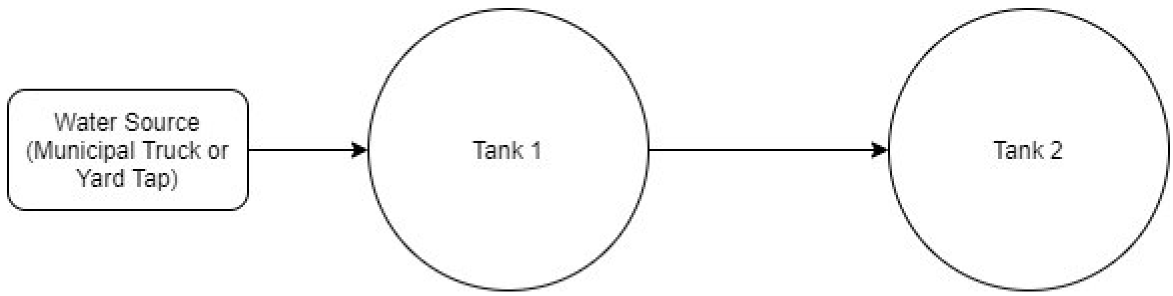

Figure 4-32: Process layout of liking of water supply tanks

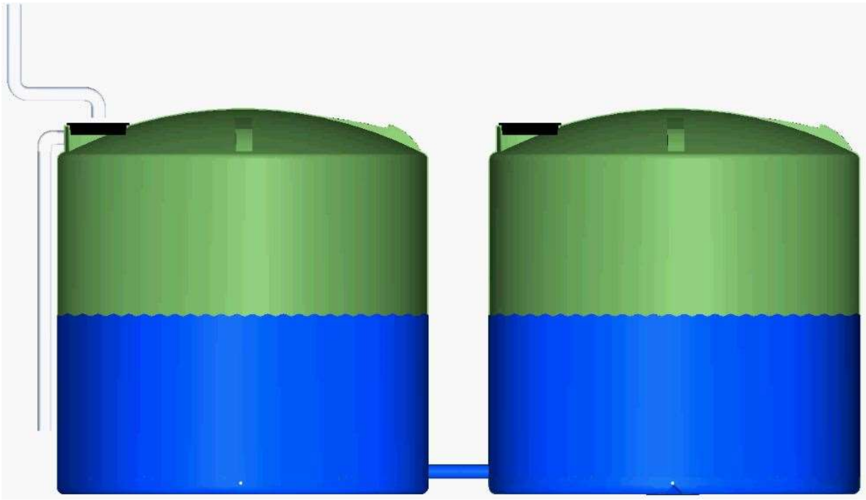

Figure 4-33: Illustration of simultaneous water tank filling

4.5.5. Project Implementation

After a comprehensive analysis of the sites and their requirements, the sanitation/biogas provision systems at the ECDCs were designed using AutoCAD. A drone was used to take aerial pictures with a reference ground scale such that they could be imported onto AutoCAD to be used to generate layout drawings with a known scale. The layout drawings were used during an iterative process of designing the system layout. Site visits and investigations were done during the iterative process and thereafter final layout drawings of the optimised biogas provision and sanitation systems at the five ECDCs. After a full design of the systems at each ECDC, a scope of works was drawn up for the management and implementation of the project. The general work elements for each site include:

- Planning the specific work elements
- Arrangement of quotations and contracting of local labour for construction of toilet blocks and removal of any old / obsolete structures
- Employment of local labour for excavation of hole for digester and other tasks such as laying of pipes, septic tank modification and other connections
- Provision of skilled plumber and gas installer
- Materials procurement, management and transport
- Testing of systems
- Project management and site supervision (quality control)

The general work elements for each site include:

- Installation of water supply system components (HDPE pipes and tanks) at sites where required (Babunene, Siyaqhubeka, Sphumelele and Ukuhlalanathi)

- Excavation of hole for digesters by local workers at required dimensions and spreading of excess earth at a selected adjacent site
- Procurement and delivery of digesters and fittings.
- Purchase and installation of sewer pipe
- Positioning of digester into excavated hole and back filling
- Fence and gate installation for digesters
- Gas line, fittings and stove installation
- Construction of soakaways
- Construction of toilet blocks at respective sites.

The components at each site were required to be installed at specific levels. The components were linked by pipes which had to be at specific slopes for specific reasons; (i) the biogas line, in order to prevent condensate water within the line and (ii) the sewer lines, in order to prevent clogging. Reference points on the sites were used to calculate the required levels which were generated on Microsoft Excel for each component within the system, as shown in Figure 4-34. The level calculation sheets can be found in Figure 7-4 to 7-8, Appendix B.

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	3	0,02		-0,06	3
2	Digester			0,09	-0,15	3
3	Pipe	0,5	0,02		-0,16	3,5
4	Septic Tank			0,09	-0,25	3,5
5	Pipe	3	0,02		-0,31	6,5
6	Soakaway			0	-0,31	6,5

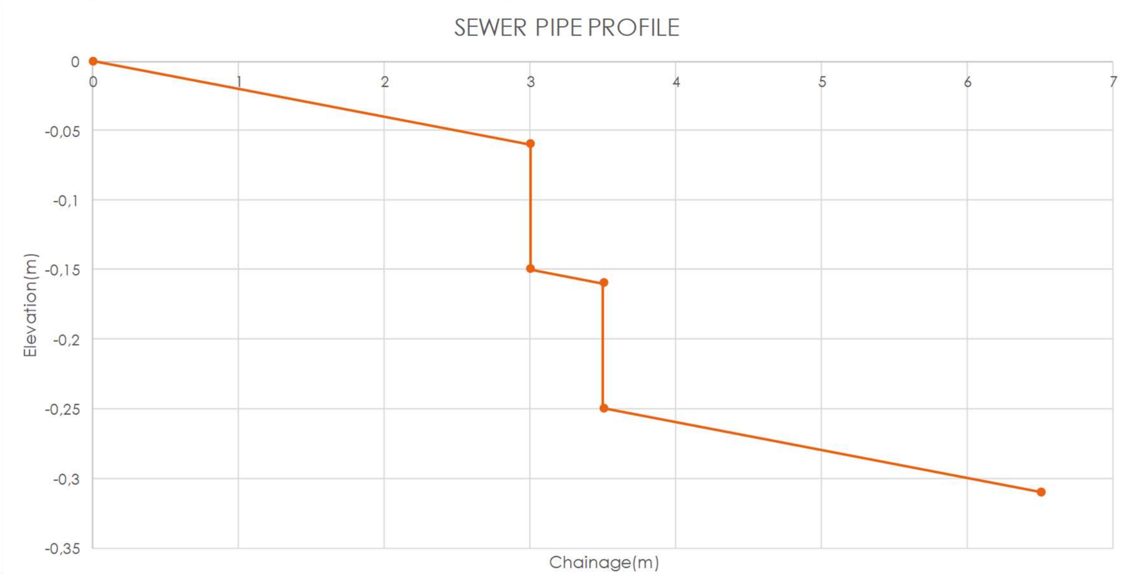

Figure 4-34: Sample excel sheet used for level estimation

Principals of lean project management were to be applied to the project to enable progress with no waste. This would enable an optimised implementation of the project. Seamless communication; All the stakeholders within the project were in constant communication and this reduced disagreement and enabled the project to flow smoothly. Zero inventory; during the project management, it was decided that items to be used on site would only be purchased and delivered just in time for installation. This alleviated the need for storage space and unnecessary transportation costs.

4.5.6. Operation, maintenance and monitoring Plan

Following the design of the systems at the five ECDCs, a plan was devised for the optimal operation, maintenance and monitoring. In terms of operation, a feeding plan was devised as shown in Table 7-2, Appendix B. The table also reveals the daily solids and liquids flow rate which was found to be below the ABP6 daily limits (refer to Product Datasheet in Appendix

B). The digesters will all be seeded with inoculum from the nearby household digesters. The feeding quantities were generated using BMP values obtained both in the lab and from literature. The available cooking hours were generated using the digester's specifications; i.e. 2m^3 can provide about 2.5 cooking hours. In addition, interviews revealed that the amount of cooking time at each ECDC was proportional to the number of students. Therefore, using Ukuhlalanathi as representative, the required cooking times were thus estimated. At worst case scenario, using the lowest BMP values, the human excreta and food waste generated will not be sufficient to operate the bio-digesters, however using the average BMP values yielded sufficient biogas volumes for cooking at each ECDC using human excreta and food waste only. It is difficult to predict the amount of biogas that will be generated from the available feedstock based on the inconsistency among BMP results therefore a future on-site assessment will reveal the true quantities of biogas generated. It is important to note that interviews revealed enthusiasm amongst the teachers at the ECDC to bring their own food waste from their homes; and children will be advised to do the same. This brings about uncertainty about the quantity of available food waste and furthermore, uncertainty still exists about the true daily human excreta mass. Therefore, the first year of school will be used to investigate the necessity of supplementary feeding with cow dung based on the true quantities of biogas generated on site.

A maintenance plan was also provided to aid the users. The maintenance plan is shown in Table 7-3, Appendix B. In terms of monitoring, only biogas quantities will be monitored using a flow meter at each ECDC.

4.5.7. Conclusion to Biogas Provision and Sanitation Systems at ECDCS.

The systems designed for the ECDCs represent an optimised anaerobic digestion process system which also functions as a sanitation system. All components of the system have been carefully selected to have a long lifespan, low maintenance and optimal performance. The results from the characterisation tests show that anaerobic digesters reduce COD and pathogens and an even higher removal efficiency will be expected when coupled with a septic tank. Furthermore, a safe disposal system has been designed to prevent any possibilities of pollution caused by residual untreated pathogens (as seen in the case of samples DG1 and DG2)

4.6. Optimised Digester Design Experiment

The digester start-up process begun within one week confirmed by the production of methane gas on this day. The initial pH values, on this day, were recorded at 7.1 and 6.9 in the prototype and control digester respectively. The final fabricated digesters have been shown in operation in Figure 4-35 and Figure 4-36 below.

Figure 4-35: Lab scale digester prototypes, control (left) and optimised (right)

Figure 4-36: Digester producing flame during operation

The two prototypes were operated successfully at an HRT of 30 days and daily gas quantity and quality were recorded, normalised and have been presented in Figure 4-37. Feeding of both digesters commenced on day 7. The cumulative gas readings over the operation of the digester were also recorded and presented in Figure 4-38 below. Daily methane readings were recorded which have been presented in Figure 4-39. Daily methane readings were not recorded on the last two days due to unavailability of the instrument. The daily carbon dioxide readings have been shown in Figure 7-10, Appendix E. The first 7 days in Figures 4-37 and 4-39 represent the start-up period where gas quality and quantity were not recorded.

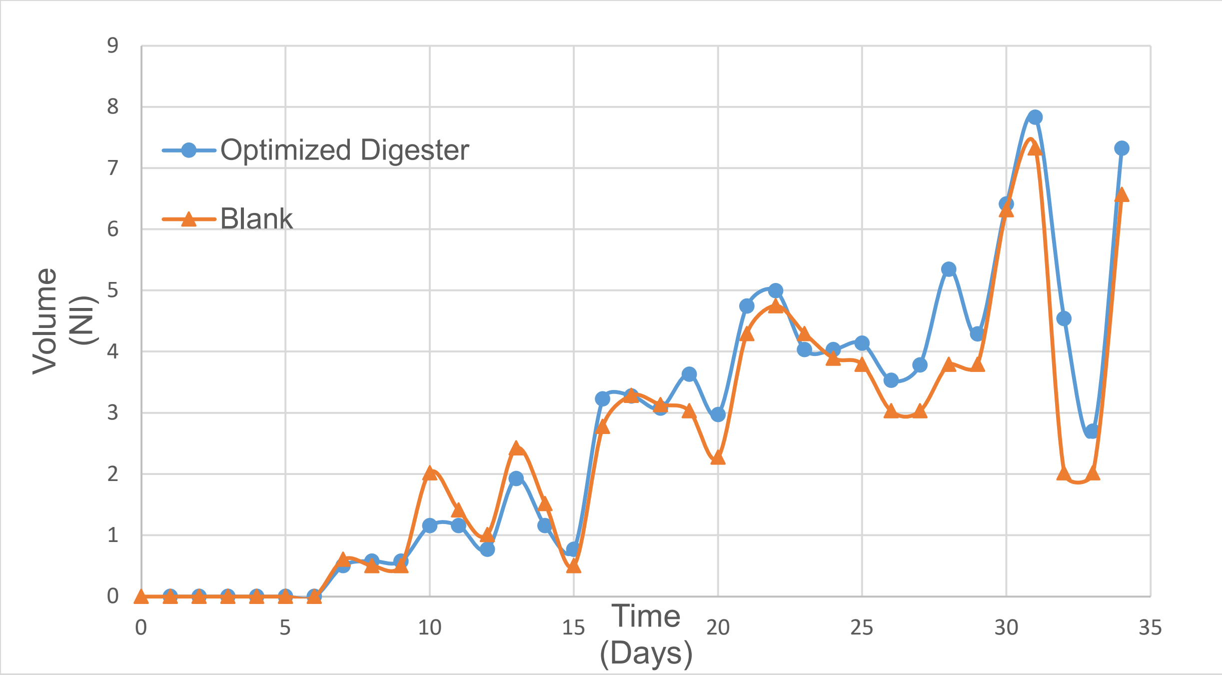

Figure 4-37: Graph showing Daily Biogas Volume against Time

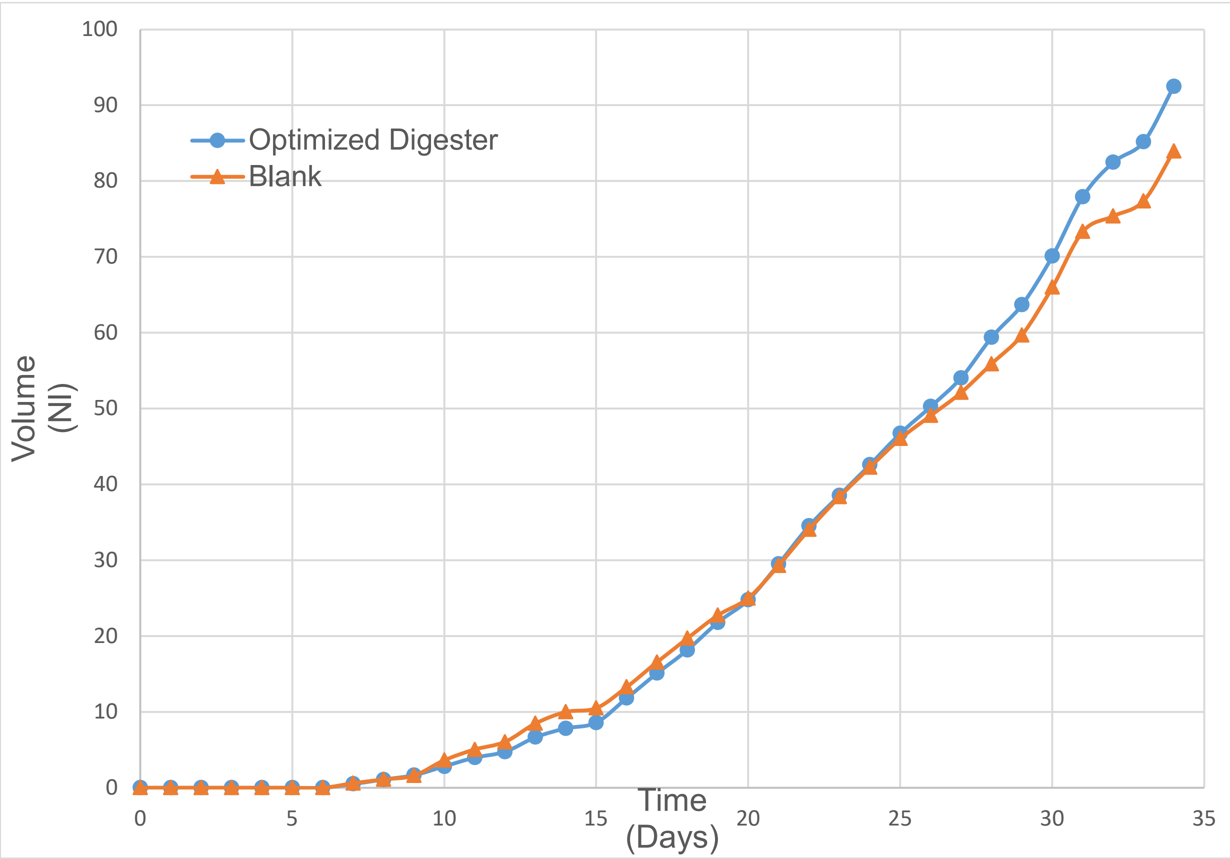

Figure 4-38: Graph showing Cumulative Biogas Volume against Time

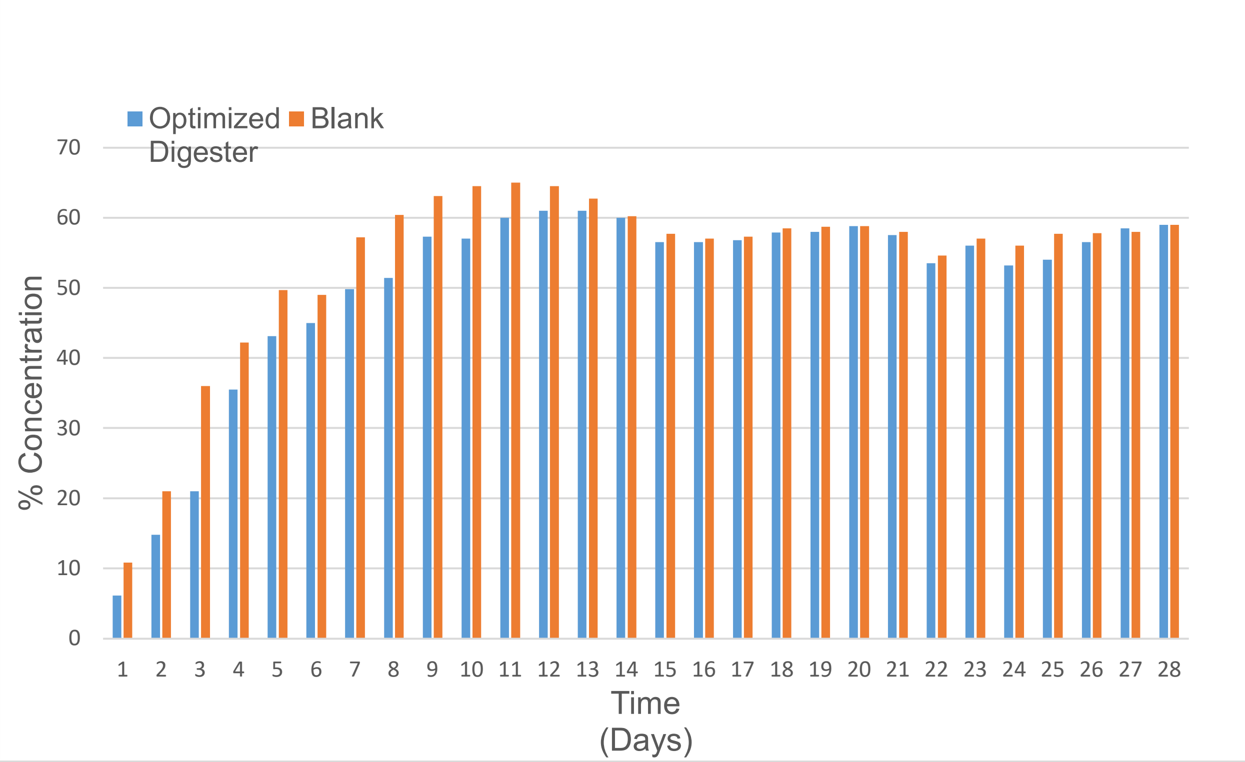

Figure 4-39: Daily Methane Concentration against Time

The control digester was observed to be producing more gas than the prototype during the first week of operation. This could be attributable to "Feature 1" on the prototype which creates temporary retention of the feedstock. The feature could have retained some of the organic matter during the first week of the experiment. As loading proceeded, however, the prototype began to produce more biogas as expected. The temporary retention mechanism seemed to have improved the gas production, by the prototype, since bacteria were able to receive feedstock more slowly than in the control digester and therefore improve biogas production.

The control digester produced slightly more methane over the first week of the testing period. This is possibly due to the fact that start-up was achieved faster in the control than in the prototype, as mentioned earlier. The methane content of both digesters steadily increased to a steady state. The methane content of both digesters slightly dropped on the last two days in Figure 4-39, when load shedding at the university occurred. Both digesters showed resilience to the change in conditions and continued to operate.

"Feature 2" on the prototype was observed to cause mixing on day using a camera that was left to record the digester. The mixing observed visually is not vigorous, as expected, but however aids in releasing biogas that is trapped in pockets within the less dense, floating digesting content. This could explain the higher biogas volumes obtained in the optimised prototype with respect to the self-mixing mechanism. Figure 4-40 shows the trapped biogas pockets and the direction of flow of air bubbles observed.

Figure 4-40: Photograph of Mixing (shown by direction of arrow) occurring due to Feature 2

4.6.1. Conclusion to Optimised Digester Experiment

Overall, the optimised digester produced 8.5L (approximately 10%) more than the control despite the redundant gas storage space. Both digesters were resilient to the high OLRs and this could be attributed to the feedstock used. The added features can be further optimised to investigate a possible improvement in the design. Computational fluid dynamics can be used to optimise such features. Furthermore, dimensional analysis can be used to upscale the prototype. Upscaling of the prototype would require a structural design; techniques such as finite element analysis can be used to optimise this structural design. An upscale prototype can be designed as a prefabricated unit using HDPE or can be constructed using brick and mortar and/or concrete. This prototype shows that the process of anaerobic digestion can be optimised using partial retention of feedstock and additional mixing. Furthermore, the solar heating temperature control mechanism (using batteries) can be up scaled and used (in conjunction with direct solar heating) to optimise temperature control in an anaerobic digester.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

This chapter serves as a conclusion to the findings presented. South Africa's rural populace faces issues related to poor service delivery which encompasses poor waste management and sanitation services as well as unsustainable energy sources. Limited research and unsustainable implementation have contributed to the infant state of biogas provision, despite its proven viability, in South Africa. Past state-sponsored projects have shown that anaerobic digestion has the potential to serve as a waste management, sanitation, and an energy option. Despite this, the anaerobic digestion process systems that have been implemented within South Africa have only been qualified successes, with a number of persistent issues arising related to the digester technologies, associated infrastructural components, maintenance, operation, and beneficiary engagement. Therefore, using a comprehensive literature review, as well as field, desktop, and laboratory analyses, an optimised practice model has been designed for 26 rural households and five ECDCs in NLM, a rural within Kwazulu-Natal, South Africa. In addition, an optimised digester design was developed based on the CFDD which produced 10% more biogas in comparison to a control.

5.2. Reflection on the Research Questions and Aims

The overall purpose of this study has been to contribute to the development of a best practice model for decentralised biogas provision within rural communities in South Africa, and KwaZulu-Natal (KZN) in particular. To this end, it adopted two principle research questions. First, considering technology, infrastructure, and process design, what is the most cost-efficient, sustainable, and reliable model for rural decentralised biogas provision within both household and institutional contexts? And, second, of the various feedstock locally available within the case study area, Ndwedwe Local Municipality, which is most analytically suitable for biogas production and contextually appropriate for project sustainability? To answer the aforementioned research questions and contribute to the overall goal of this study, the following aims were identified:

1. To evaluate the performance and compare the technical specifications of micro-digester technologies available within South Africa.
2. To assess the performance of 26 household anaerobic digestion process systems installed in the NLM area based on the technology, process, and infrastructural components.

3. To develop and implement an optimisation plan for the aforementioned 26 digester systems which addresses identified weaknesses and contributes to the long-term sustainability of the interventions.
4. To identify and characterise locally available feedstock and propose ideal feeding regimens for specific biogas interventions.
5. To design and implement an optimised integrated biogas provision and sanitation system at five ECDCs in NLM in order to evaluate the energy and sanitation outcomes of such an intervention.
6. To evaluate the socio-economic impacts of biogas interventions within rural South African households and institutions.
7. To develop and test an optimised lab-scale anaerobic biogas digester design which can be utilised within rural South African contexts.

These aims guided the data analysis which is thoroughly presented in Chapter Four. The first aim was addressed within the literature review (Chapter Two). Chapter 2.8 and Chapter 2.13 provide an assessment of the main types of digesters, as well as the digester types supplied by different developers respectively. The CFDD was found to be the most suitable digester type for rural areas in South Africa based on its long lifespan, local availability of construction materials (when necessary), cost of construction, ease of operation, ease and cost of maintenance, efficiency, feasibility of insulation, and reliability. Amongst the developers of digester types in South Africa, two CFDD designs (the "Puxin" Digester and the ABP6) were selected to be most suitable for rural South African areas. The Puxin digester is a suitable option due to its ease of construction and operation, and, similar to the ABP6, its constant biogas pressure and relatively long lifespan. However, the Puxin digester's size (10m^3) may be too large for small scale purposes, and in addition, its construction costs may be high. AGAMA's 6m^3 digester (ABP6), however, is available at a suitable size, especially for small scale rural applications. In addition, the ABP6 prefabricated design enables quick installation and eliminates possible construction complications. The price of the AGAMA 6m^3 digester was reported to be high in the past, however, its installation requires minimal labour so it may be an overall cheaper technology than the "Puxin" digester. Furthermore, the price of the AGAMA 6m^3 digester has not changed since its inception (in 2008) which makes it relatively cheaper now considering the inflation over the years. In addition, it has been designed to treat sewage more efficiently (see Section 4.5.3.1.), and therefore may serve as an ideal option for biogas sanitation systems. Both designs however have limited agitation and are dependent on the ground temperature for insulation, since they are both installed underground (Mutungwazi et al., 2018). An optimised digester, which is discussed later, was developed to improve the CFDDs performance.

The second and third aims were addressed within Chapter 4.3. Results suggests that the CFDDs, installed at the respective NLM households, are largely successful at producing viable gas using locally available feedstock, however persistent infrastructural issues related to the delivery of gas to the home have severely impacted the success of the interventions. Over the five-year period, 20 out of the 26 digesters were still producing gas, and out of the six dysfunctional ones, one had a structural failure (cracks due to settlement of soil below slab) and one had a burnt dome. The other four anaerobic digesters were not functioning due to irreparably damaged or removed gas outlet valves. To improve probability of airtightness, one should use a waterproofing admixture to the mortar mix used for its construction. Installation should also be done carefully to prevent settlement of soil below the digester's slab which causes leaks. This shows that if a CFDD is installed and maintained correctly, it will have a long life-span, however close attention should be paid to the optimisation of the system components to promote sustainable supply of biogas. An optimised process flow chart for the households was developed. Within the optimised household digestion process system: 1) all toilets were to be connected to the digester, where necessary, to treat human excreta, 2) all system components were replaced with more sustainable components that is to say; robust long lasting HDPE grey water pipes, corrosion resistant stoves and an improved biogas pipeline 3) A biogas flow meter was added to indicate available biogas quantity (may only be added if financially viable and feedstock is limited) and finally 4) soakaways to enable sanitary disposal of digestate.

The fourth aim of this study was to identify and characterise locally available feedstock and propose ideal feeding regimens for the specific biogas interventions under investigation. This aim was addressed in Chapter 4, which provides an analysis of the bio-chemical characteristics and BMP of locally available feedstock. Food waste had the highest BMP of 302.2 Nl/kg.VS, followed by cow dung (216.7 Nl/kg.VS), and finally human excreta (199.20 Nl/kg.VS). This was expected based on their respective COD, RI_7, and VS content, which indicate content of biodegradable matter. In addition, the BMP values were found to be in range with values provided (Castro et al., 2017; Mang, 2010; Mang and Li, 2010; Rosenberg and Kornelius, 2017; Samson et al., 2018; Widiasa et al., 2009; Zhang et al., 2007). However, as Section 3.8.5 describes, there are a number of inconsistencies within the body of literature, therefore values should be compared in order to provide a more accurate indication of the BMP. Despite the high BMP of food waste, on analysis, cow dung was determined to be the most bio-chemically ideal feedstock due to its stability during anaerobic digestion. This stability is due to cow dung's ideal C/N ratio (measured to be 30.86:1) as well as its notable buffering capacity. Food waste exhibited a high VFA/TA ratio (measured to be 0.8), and indeed went sour during the initial BMP test attempt, however sufficient alkalinity was added and the food waste BMP test was able to be restarted. This experience shows the poor buffering capacity of food waste, which may necessitate co-digestion with other substrates, pre-treatment, or the use of a multi-stage digester. Human excreta had the highest extent of pathogen pollution, which supports the need for its sanitary treatment and disposal. Characterisation tests were also performed on two samples of household digestate, one from a digester fed with human excreta, food waste, and cow dung, and the other fed with only the latter two substrates. Both digestate samples had COD and pathogen indicator values beyond the disposal limits prescribed by the National Water Act and Water Research Commission (2009); this necessitates either further treatment, or the sanitary disposal of the digestate. However, significant reductions, up to 99%, of E*nterococci, Faecal streptococci. Faecal Coliforms* and *E.Coli* were observed after the BMP test. This shows anaerobic digestion's utility as part of an integrated sanitation and energy system, in its ability to reduce the aforementioned pathogen concentrations. As described in Section 4.5.6, a feeding regimen was developed in order to assist the ECDCs in the regular upkeep of their digesters in order to meet daily biogas needs. However, a number of uncertainties have necessitated delay in the implementation of such a regimen until further data can be collected. As noted, due to the unreliability of BMP data in literature, it is difficult to predict the amount of biogas that will be generated from the available feedstock. Although a quantification and characterisation of daily food waste occurred, interviews revealed enthusiasm amongst the teachers and students at the ECDC to bring their own food waste from their homes. Therefore, daily amounts may fluctuate significantly, depending on the dedication of beneficiaries. Significant uncertainty also exists about the true daily human excreta mass, and because it was not possible to measure this on site, estimates were based on values from literature. Therefore, following implementation of the biogas interventions the first year of monitoring and evaluation should be used to investigate the suitability of these two feedstock, and the necessity of supplementary feeding with cow dung based on the true quantities of biogas generated on site. In regards to the SANEDI households, having an adequate supply of cow dung available was a criterion for beneficiary selection (possession of minimum of two cows). Therefore, in these contexts, ideal feedstock is both accessible and abundant; therefore, the design of a specific feeding regimen was not deemed necessary.

The fifth aim has been achieved in Chapter 4.5 where an optimised biogas provision and sanitation system has been designed for five ECDCs in the NLM area. An optimised anaerobic digestion process system flow chart to be used for the five ECDCs has been shown in Section 4.5.2. The systems designed for the ECDCs represent an optimised anaerobic digestion process system which also functions as a sanitation system. All components of the system have been carefully selected to have a long lifespan, low maintenance, and optimal performance. These components include: the ABP6 anaerobic digester, pour flush toilets, ceramic burner stoves, HDPE water supply and greywater pipes, reliable water supply systems (Section 4.5.4), flow metres, and hydrogen sulphide scrubbers. Pour flush toilets use two litres per flush compared to the conventional five to nine litres per flush; this will reduce dilution of the human excreta and hence improve its digestion, as well as save water. Despite the fact that hydrogen sulphide functions as an indicator of biogas leaks, field analyses on the household digester revealed concentrations higher than 50ppm which will be detrimental to children's health. The results from the characterisation tests show that anaerobic digesters reduce COD (as high as 76% removal efficiency) and pathogen indicators: *enterococci, Escherichia Coli, Faecal Streptococci* and *Faecal Coliforms* (99% removal efficiency). Therefore, an even higher removal efficiency will be expected when coupled with a septic tank, as shown by similar biogas sanitation systems. Furthermore, safe disposal systems have been designed (soakaways and reedbeds) to prevent any possibilities of pollution caused by any possible residual untreated pathogens (as seen in the case of the household digestate samples). A maintenance and troubleshooting plan was also provided to the ECDCs to promote sustainability of the optimised anaerobic digestion process systems. Sanitation outcomes have been predicted as shown by the removal efficiencies while energy outcomes in terms of BMP were discussed earlier. Future on-site investigations will provide answers to the true energy and sanitation outcomes of the systems.

Chapter 4 addresses the socio-economic aspect of the rural biogas interventions. This information was obtained using interviews. The households reported positive socio-economic feedback based on the interviews conducted. The information showed that the household beneficiaries had monetary savings from energy expenses after the biogas interventions. The correspondence also showed that people had gained interest in the technology, and evidence of this is shown by ECDCs desiring to acquire biogas provision systems. One of the household beneficiaries reported initial apprehension at the idea of using waste to produce gas for cooking food. This is an important social aspect that contributes to cultural-social stigma and traditional taboo that could affect the adoption of this technology and could potentially affect the widespread promotion and adoption of the biogas technology.

Lastly, an optimised digester prototype was designed and tested based on the CFDD. The aim of this experiment was to provide optimisations to the CFDD to enable it to perform optimally under higher OLRs (which can be expected at larger rural institutions) while still retaining its strength, ease and cost of operation and maintenance, efficiency, feasibility of insulation, and reliability. Additionally, as mentioned earlier, CFDDs are associated with limited agitation. Therefore, two features that enable partial retention of feedstock during digestion (to prevent shock loading onto the methanogenic microorganisms) and self-agitation were added. The optimised digester prototype produced 8.5L (approximately 10%) more than a control despite a redundant gas storage space and high OLR of 3.4kgVS/m^3/day. In addition, the prototypes were designed as one unit with the expansion chambers above the reactive chambers to enable constant biogas pressure and possible fabrication as one unit (rather than assemblage of an inlet and outlet chambers, possible pipes and a reactive tank). More testing can be performed before an upscaling process for example at different HRT and with perhaps more replicates. Dimensional analysis can be used to upscale the prototype for use at rural institutions. Upscaling of the prototype would require a structural design; techniques such as finite element analysis can be used to optimise this structural design. An upscale prototype can be designed as a prefabricated unit using HDPE or can be constructed using brick and mortar, if necessary, or concrete. Overall, the omission of pipes and the "single-unit" design would ease a structural optimisation. This prototype shows that the process of anaerobic digestion can be optimised using the aforementioned techniques which enable partial retention of feedstock during digestion (to prevent shock loading onto the methanogenic microorganisms) and self-agitation. Furthermore, the proposed solar heating temperature control mechanism (using batteries) can be up-scaled and used (in conjunction with direct solar heating using a thermosiphon or DC solar heater) to optimise temperature control in an anaerobic digester.

To reflect on the overall research questions, considering technology, infrastructure, and process design, what is the most cost-efficient, sustainable, and reliable model for rural decentralised biogas provision within both household and institutional contexts? This dissertation presented an optimised reliable model for biogas provision within both household and institutional contexts in the form of a full design at five ECDCs as well as a process system design for households that includes optimised infrastructural components. Infrastructural components were replaced with optimised components that included: robust material pipelines, corrosion-resistant stoves, hydrogen sulphide scrubbers, pour flush toilets, and a prefabricated CFDD (selected as the most suitable for the context among the South African options). Analysis suggests that the CFDD would be the most suitable for a rural community due to its long lifespan, availability of construction materials in the locality (when necessary), cost of construction, ease of operation, ease and cost of maintenance, efficiency, feasibility of insulation, and reliability. However, CFDDs are restricted to a minimum OLR and therefore its performance may be compromised if used at a larger institution. Therefore, an optimised prototype, based on the CFDD was designed and proved to produce 10% more biogas at a higher OLR, despite a redundant gas storage space, when compared to a control.

Second, of the feedstock locally available within the case study area, NLM, which are most analytically suitable for biogas production and contextually appropriate for project sustainability? Cow dung has shown to be the most bio-chemically suitable feedstock amongst the locally available feedstock in NLM because of its stability during the anaerobic digestion process (as a result of sufficient buffering capacity and ideal C/N ratio) and its relatively high BMP value obtained from BMP test. Food waste had the highest BMP value obtained from the BMP test, however, co-digestion with human excreta or cow dung should be considered to supplement the lacking buffering capacity of food waste. Unsanitary disposal of human excreta poses the greatest threat to humans as shown by its relatively high pathogen content. Anaerobic digestion has been shown to reduce up to 99% of pathogen content, however, field digester effluents still showed a prevailing content of pathogens which necessitate its sanitary disposal. Human excreta, despite having the lowest BMP, can be treated successfully through a well-designed biogas provision and sanitation system; this can provide biogas for cooking and alleviate the detrimental effects of its potential pollution. Furthermore, if human excreta, food waste, and cow dung (if available) are co-digested, they can provide sufficient amounts of biogas for cooking while providing sanitary management of such organic waste.

5.3. Recommendations for Future Research

A field investigation is recommended in the future to assess the optimisations applied to the NLM households and the five ECDCs. This would speak to the success of the interventions applied to both cases. Moreover, such an investigation would provide definite removal efficiencies of the COD and pathogen pollutants by the ECDCs anaerobic digestion process systems. Furthermore, such an assessment would enable measurement of the sustainability of the optimisations applied to the anaerobic digestion process systems. Additionally, the digester prototype can be optimised even further using techniques such as computational fluid dynamics. The digester can also be used to investigate real life feeding regimes which can provide a comparison between BMP and real life biogas quantity and quality.

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7. APPENDICES

7.1. Appendix A: Interviews at NLM Household Beneficiaries:

This appendix contains all the interviews that were carried out at the NLM households

Interview with Correspondent A

METHODOLOGY

General information on biogas (from an energy perspective)

Introduction

Hello, my name is Jonathan Olal Ogwang , a final year civil engineering student at the University Of Kwazulu Natal 26 biogas digesters have been installed in Ndwedwe and I am tasked with assessing the feasibility of using biogas as an energy solution for the rural areas SANEDI is interested in how these biogas digesters they installed have fared over the years This enable us to deduce how well biogas technology has performed It will also enable us to identify the gaps in the system and rectify them accordingly It will also enable us to find out whether we can explore using this technology in rural areas

Your responses will be kept confidential at all times. Your personal details are not required for this study Your participation is voluntary and you may withdraw your permission to participate at any stage

Background Information

1. How long have you lived in the area? (Year) - 60 years
2. How large is your household? - 5 people
3. What is your occupation and what are your household's sources of cash income?

   Sangoma

4. What do you think of biogas as a solution to your energy needs? - Very good solution.
5. When was your biogas digester installed? -
6. How often do you use your biogas digester? - Everyday before it broke down.
7. Is your biogas digester still functioning? - No.
8. If it has stopped functioning, how many years or months was it working? - 6 months
9. What are the reasons why your digester is (either) still working/stopped working? - N/A .
10. What did you do about the digester when it stopped working?

    Did not do anything but

11. What are the reasons?

    Did not have knowledge

12. What do you use your biogas for? - Cooking & lighting .
13. Did you know that biogas can have other uses?

    Not until Khanyisa personell intervened

14. Is the gas enough?
It was enoughs except for cooking beans.

15. Were you aware of biogas technology before it was introduced to your household?
No!

16. How did you come to know about biogas technology, if so?
N/A.

17. Did SANEDI educate you about biogas before installing the system for you? - Yes
18. How useful was their information?
Very useful but not everything was understood.

19. What reasons led to your consideration of using biogas?
It was free.

20. Did you find the technology technically demanding?(Was operation and maintenance difficult?) - Yes, because it was so new.

21. If yes, what aspects of this technology requires more technical assistance
Maintenance.

22. Were you trained on the maintenance of the biogas system? - No.
23. Did/do you receive a service technician? - Yes
24. Is/was the service technician readily available when you need them? (If provided anyway) - No.
25. How much did you contribute towards the installation? ZARO
26. Who contributed the rest and how much? - SANEDI
27. Did you feel the cost was affordable to you, including maintenance? (a) Yes ...... (b) No... - N/A.
28. If not, what were the reasons? - N/A.

14. Is the gas enough?
It was enough except for cooking beans.

15. Were you aware of biogas technology before it was introduced to your household?
No!

16. How did you come to know about biogas technology, if so?
N/A.

17. Did SANEDI educate you about biogas before installing the system for you? - Yes
18. How useful was their information?
Very useful but not everything was understood.

19. What reasons led to your consideration of using biogas?
It was free.

20. Did you find the technology technically demanding?(Was operation and maintenance difficult?) – Yes, because it was so new.

21. If yes, what aspects of this technology requires more technical assistance
Maintenance.

22. Were you trained on the maintenance of the biogas system? – No.
23. Did/do you receive a service technician? - Yes
24. Is/was the service technician readily available when you need them? (If provided anyway) – No.
25. How much did you contribute towards the installation? ZARO
26. Who contributed the rest and how much? – SANEDI
27. Did you feel the cost was affordable to you, including maintenance? (a) Yes ...... (b) No... – N/A.
28. If not, what were the reasons? – N/A.

iv. ....
v. ....
vi. ....

3. Have other people gained interest in biogas since they saw your system in place? – Yes!
4. What were your main sources of energy before introduction of biogas? List in order of importance
   i. LPG gas ....
   ii. Firewood ....
   iii. Paraffin ....
   iv. ....
   v. ....
   vi. ....

5. How much fuel-wood (Charcoal or fire-wood), paraffin, LPG gas, electricity or other sources of energy were you spending monthly and the total cost (including time spent) before and after installing the biogas digester (ZAR)?

Source	Before	After	Difference
Charcoal			N/A
Fire-wood			No more firewood was collected while using the technology
Paraffin			No more paraffin was used while biogas was available
LPG Gas			Still buy it incase but in lower quantities.
Electricity			
Other source			
Other source			
Total			

Interview with Correspondent B

Mrs. Mhlongwini Ixkumu. A2

METHODOLOGY

General information on biogas (from an energy perspective)

Introduction

Hello, my name is Jonathan Olal Ogwang , a final year civil engineering student at the University Of Kwazulu Natal 26 biogas digesters have been installed in Ndwedwe and I am tasked with assessing the feasibility of using biogas as an energy solution for the rural areas SANEDI is interested in how these biogas digesters they installed have fared over the years This enable us to deduce how well biogas technology has performed It will also enable us to identify the gaps in the system and rectify them accordingly It will also enable us to find out whether we can explore using this technology in rural areas

Your responses will be kept confidential at all times. Your personal details are not required for this study Your participation is voluntary and you may withdraw your permission to participate at any stage

Background Information

1. How long have you lived in the area? (Year) – 64 years.
2. How large is your household? – 17 people
3. What is your occupation and what are your household's sources of cash income?
   Pension & children.
4. What do you think of biogas as a solution to your energy needs? – Very Good solution.
5. When was your biogas digester installed? –
6. How often do you use your biogas digester? – everyday.
7. Is your biogas digester still functioning? – Yes
8. If it has stopped functioning, how many years or months was it working? – No!
9. What are the reasons why your digester is (either) still working/stopped working? – N/A.
10. What did you do about the digester when it stopped working?
    N/A.
11. What are the reasons?
    N/A
12. What do you use your biogas for? – Cooking, fertilizer.
13. Did you know that biogas can have other uses? – Not until intervention

14. Is the gas enough? – Yes!

15. Were you aware of biogas technology before it was introduced to your household?
Yes, !

16. How did you come to know about biogas technology, if so?
From a friend.

17. Did SANEDI educate you about biogas before installing the system for you? - Yes but not directly.
18. How useful was their information?
Very useful.

19. What reasons led to your consideration of using biogas?
It was free.

20. Did you find the technology technically demanding?(Was operation and maintenance difficult?) – NO!

21. If yes, what aspects of this technology requires more technical assistance
NO!

22. Were you trained on the maintenance of the biogas system? - ~~Yes~~ No.
23. Did/do you receive a service technician? – Yes
24. Is/was the service technician readily available when you need them? (If provided anyway) – NO!
25. How much did you contribute towards the installation? ZARO
26. Who contributed the rest and how much? SANEDI
27. Did you feel the cost was affordable to you, including maintenance? (a) Yes …… (b) No… – N/A.
28. If not, what were the reasons? – N/A.

14. Is the gas enough? – Yes!

15. Were you aware of biogas technology before it was introduced to your household?
Yes, !

16. How did you come to know about biogas technology, if so?
From a friend.

17. Did SANEDI educate you about biogas before installing the system for you? - Yes but not directly.
18. How useful was their information?
Very useful.

19. What reasons led to your consideration of using biogas?
It was free.

20. Did you find the technology technically demanding?(Was operation and maintenance difficult?) – NO!

21. If yes, what aspects of this technology requires more technical assistance
NO!

22. Were you trained on the maintenance of the biogas system? – ~~Yes~~ No.
23. Did/do you receive a service technician? – Yes
24. Is/was the service technician readily available when you need them? (If provided anyway) – NO!
25. How much did you contribute towards the installation? ZARO
26. Who contributed the rest and how much? SANEDI
27. Did you feel the cost was affordable to you, including maintenance? (a) Yes …… (b) No… – N/A.
28. If not, what were the reasons? – N/A.

iv. ....
v. ....
vi. ....

3. Have other people gained interest in biogas since they saw your system in place?— Very much so!
4. What were your main sources of energy before introduction of biogas? List in order of importance
   i. Same as Juma ....
   ii. ....
   iii. ....
   iv. ....
   v. ....
   vi. ....

5. How much fuel-wood (Charcoal or fire-wood), paraffin, LPG gas, electricity or other sources of energy were you spending monthly and the total cost (including time spent) before and after installing the biogas digester (ZAR)?

Source	**Before**	**After**	**Difference**
Charcoal	— Same as Juma.		
Fire-wood			
Paraffin			
LPG Gas			
Electricity			
Other source			
Other source			
Total			

Interview with Correspondent C

METHODOLOGY

General information on biogas (from an energy perspective)

Introduction

Hello, my name is Jonathan Olal Ogwang , a final year civil engineering student at the University Of Kwazulu Natal 26 biogas digesters have been installed in Ndwedwe and I am tasked with assessing the feasibility of using biogas as an energy solution for the rural areas SANEDI is interested in how these biogas digesters they installed have fared over the years This enable us to deduce how well biogas technology has performed It will also enable us to identify the gaps in the system and rectify them accordingly It will also enable us to find out whether we can explore using this technology in rural areas

Your responses will be kept confidential at all times. Your personal details are not required for this study Your participation is voluntary and you may withdraw your permission to participate at any stage

Background Information

1. How long have you lived in the area? (Year) – 26 years.
2. How large is your household? – 5 people for her alone (husband has other wives)
3. What is your occupation and what are your household's sources of cash income?

   Pension & husband

4. What do you think of biogas as a solution to your energy needs? – Very Good.
5. When was your biogas digester installed? –
6. How often do you use your biogas digester? – Everyday for fertilizer & everyday while it worked
7. Is your biogas digester still functioning? – No!
8. If it has stopped functioning, how many years or months was it working? – 1 year.
9. What are the reasons why your digester is (either) still working/stopped working? – clogged pipes.
10. What did you do about the digester when it stopped working?

    – Nothing

11. What are the reasons?

    No knowledge.

12. What do you use your biogas for? – Fertilizer & cooking
13. Did you know that biogas can have other uses?

    Not until intervention.

14. Is the gas enough? - Yes

15. Were you aware of biogas technology before it was introduced to your household?

NO!

16. How did you come to know about biogas technology, if so?

N/A

17. Did SANEDI educate you about biogas before installing the system for you? - Yes
18. How useful was their information?

Good

19. What reasons led to your consideration of using biogas?

It was free.

20. Did you find the technology technically demanding?(Was operation and maintenance difficult?)

Yes!

21. If yes, what aspects of this technology requires more technical assistance

↳ Maintenance.

22. Were you trained on the maintenance of the biogas system? — NO!
23. Did/do you receive a service technician? - Yes
24. Is/was the service technician readily available when you need them? (If provided anyway) — NO!
25. How much did you contribute towards the installation? ZAR0
26. Who contributed the rest and how much? SANEDI
27. Did you feel the cost was affordable to you, including maintenance? (a) Yes ...... (b) No.... N/A
28. If not, what were the reasons?

N/A

29. What main type of biodegradable raw material(s) (e g dung) have you been using to feed the digester and where do you obtain them from?

Cow dung from kraal.

30. Are/were the biodegradable raw material(s) easily available?- Yes.
31. Have you considered using other materials?

No!

32. Are/were the materials enough for your daily feeding of the digester?

Yes!

33. What water do you use to feed the system and is it sufficient? - Grey Water.
34. If not how and from where do/did you obtain the rest of the water?

N/A -

35. How often do you feed the digester and what quantity each time? - Everyday
36. How often do you need to empty/clean your digester if need-be? - Never
37. What are the technical problems that you experience with your digester, if any (e g leakage)?

Pipes being clogged when was identified at the day of the visit.

38. Are there other problems that you think affect the success of your biogas technology?

Maintenance skills.

39. Do the pipes get clogged?

Yes.

Socio-economic and cultural issues

1. Are there social taboos associated with the raw materials you use?

Yes!

If yes, please explain

Some people expressed disgust.

2. What are the benefits you have obtained after adopting the biogas technology? List in order of importance
   i. ....Same for all correspondents. ....
   ii. ....
   iii. ....

iv. ....
v. ....
vi. ....

3. Have other people gained interest in biogas since they saw your system in place? – Yes!
4. What were your main sources of energy before introduction of biogas? List in order of importance
   i. ....
   ii. → Same as all correspondents ....
   iii. ....
   iv. ....
   v. ....
   vi. ....

5. How much fuel-wood (Charcoal or fire-wood), paraffin, LPG gas, electricity or other sources of energy were you spending monthly and the total cost (including time spent) before and after installing the biogas digester (ZAR)?

Source	Before	After	Difference
Charcoal			
Fire-wood	→ Same for all		
Paraffin			
LPG Gas			
Electricity			
Other source			
Other source			
Total			

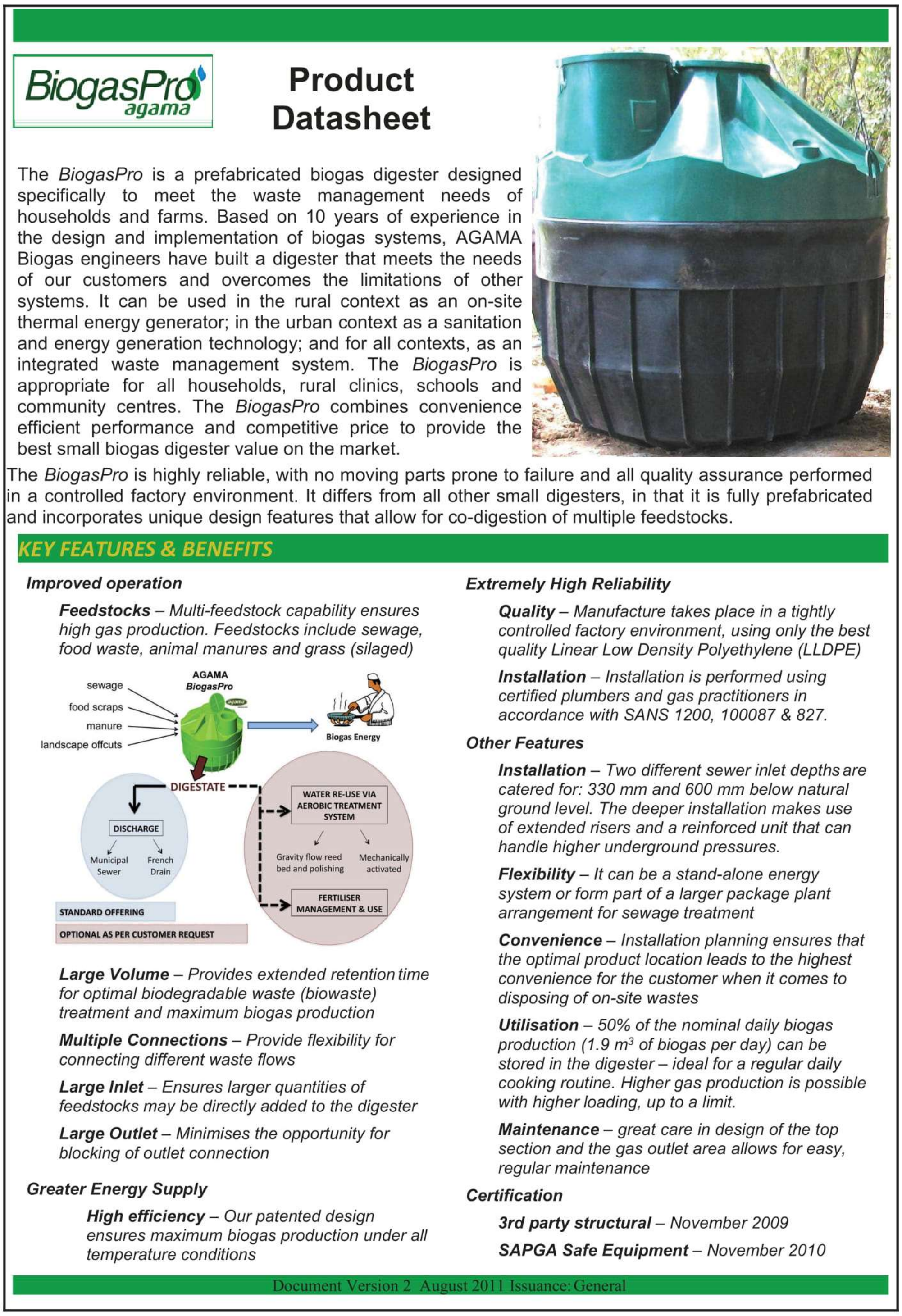
7.2. Appendix B: Interventions at the NLM ECDCs

This appendix contains all the information regarding the ECDCs at NLM that is referred to within the text.

Figure 7-1: Meal timetable at Ukuhlalanathi ECDC

Table 7-1: Daily food waste quantities at Ukuhlalanathi ECDC, over 64 days.

DAY	WEIGHT (KG)	DAY	WEIGHT (KG)	
1	3,88	33	4,7	**Start Date: 2019/08/28**
2	7,44	34	4,3	**End Date: 2019/12/03**
3	8,25	35	4,1	
4	5,76	36	5,31	
5	4,39	37	3,71	
6	5,12	38	4,9	
7	6,03	39	4,9	
8	5,01	40	4,6	
9	5,07	41	5	
10	3,13	42	3,8	
11	3,16	43	4,6	
12	6,51	44	5,1	
13	4,75	45	4,5	
14	3,12	46	5	
15	2,09	47	3	
16	2,17	48	4,2	
17	4,6	49	4,9	
18	3,4	50	4	
19	5,84	51	5,08	
20	3,29	52	3,9	
21	4,29	53	5,2	
22	5,71	54	5	
23	4,76	55	4,7	
24	3,4	56	5,3	
25	4,75	57	3,1	
26	3,25	58	5,4	
27	1,4	59	5,31	
28	2,05	60	4,91	
29	4,31	61	18,4	
30	4,52	62	5,9	
31	5	63	2,3	
32	3	64	2	



Product Datasheet

The *BiogasPro* is a prefabricated biogas digester designed specifically to meet the waste management needs of households and farms. Based on 10 years of experience in the design and implementation of biogas systems, AGAMA Biogas engineers have built a digester that meets the needs of our customers and overcomes the limitations of other systems. It can be used in the rural context as an on-site thermal energy generator; in the urban context as a sanitation and energy generation technology; and for all contexts, as an integrated waste management system. The *BiogasPro* is appropriate for all households, rural clinics, schools and community centres. The *BiogasPro* combines convenience efficient performance and competitive price to provide the best small biogas digester value on the market.

The *BiogasPro* is highly reliable, with no moving parts prone to failure and all quality assurance performed in a controlled factory environment. It differs from all other small digesters, in that it is fully prefabricated and incorporates unique design features that allow for co-digestion of multiple feedstocks.

KEY FEATURES & BENEFITS

Improved operation

Feedstocks – *Multi-feedstock capability ensures high gas production. Feedstocks include sewage, food waste, animal manures and grass (silaged)*

Large Volume – *Provides extended retention time for optimal biodegradable waste (biowaste) treatment and maximum biogas production*

Multiple Connections – *Provide flexibility for connecting different waste flows*

Large Inlet – *Ensures larger quantities of feedstocks may be directly added to the digester*

Large Outlet – *Minimises the opportunity for blocking of outlet connection*

Greater Energy Supply

High efficiency – *Our patented design ensures maximum biogas production under all temperature conditions*

Extremely High Reliability

Quality – *Manufacture takes place in a tightly controlled factory environment, using only the best quality Linear Low Density Polyethylene (LLDPE)*

Installation – *Installation is performed using certified plumbers and gas practitioners in accordance with SANS 1200, 100087 & 827.*

Other Features

Installation – *Two different sewer inlet depths are catered for: 330 mm and 600 mm below natural ground level. The deeper installation makes use of extended risers and a reinforced unit that can handle higher underground pressures.*

Flexibility – *It can be a stand-alone energy system or form part of a larger package plant arrangement for sewage treatment*

Convenience – *Installation planning ensures that the optimal product location leads to the highest convenience for the customer when it comes to disposing of on-site wastes*

Utilisation – *50% of the nominal daily biogas production (1.9 m^3 of biogas per day) can be stored in the digester – ideal for a regular daily cooking routine. Higher gas production is possible with higher loading, up to a limit.*

Maintenance – *great care in design of the top section and the gas outlet area allows for easy, regular maintenance*

Certification

3rd party structural – *November 2009*

SAPGA Safe Equipment – *November 2010*

Document Version 2 August 2011 Issuance: General

Figure 7-2: ABP6 product datasheet, page 1

TECHNICAL SPECIFICATIONS

Mechanical specifications

- *Reactor volume: 4,050 litres*
- *Gas store volume: 950 litres*
- *Expansion volume: 1,000 litres*
- *Total volume: 6,000 litres*
- *Access chambers: 520 mm diameter*
- *Max gas pressure: 6.75 kPa*
- *Dimensions - BiogasPro-6:*
  - *Diameter: 2,160 mm*
  - *Height: 2,225 mm*
  - *Weight: 230 kg*
  - *Wall thickness: 8 – 11 mm*
  - *Sewer inlet depth: 330 mm*
- *Dimensions - BiogasPro-6D:*
  - *Diameter: 2,160 mm*
  - *Height: 2,525 mm*
  - *Weight: 300 kg*
  - *Wall thickness: 8 – 11 mm*
  - *Sewer inlet depth: 600 mm*

Environmental specifications

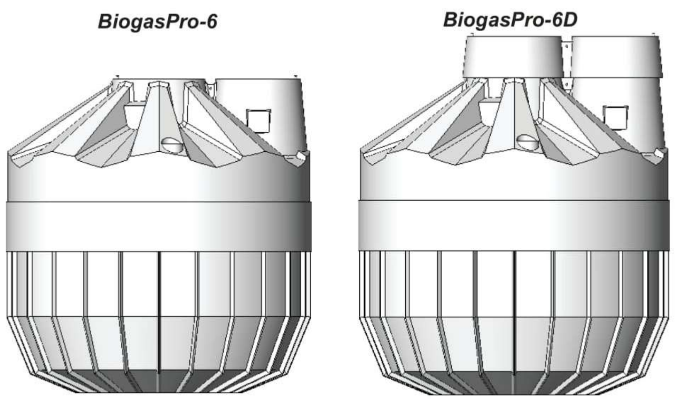
- *Operating temperature: +10 °C to +40 °C*
- *COD reduction: 50% – 98% (feedstock and loading conditions dependent)*

Loading specifications

- *Feeding rates are feedstock and temperature dependent. A maximum of 1,000 litres of water can be added daily.*
- *Expect a difference in gas production between winter and summer months. Loading should be reduced in winter to account for the slower biological activity*
- *Daily loading limits*
  - *Cow Manure 50 kg/day*
  - *Food waste 35 kg/day*
  - *Grass Silage 25 kg/day*
- *The minimum ratio of fresh feedstock to water is 1:1*

Energy specifications

- *Biogas production is proportional to the amount of feedstock and operating temperature*
- *Biogas contains approximately 60% methane (CH_4), 39% carbon dioxide (CO_2) and 1% hydrogen sulphide (H_2S)*
- *Each cubic metre of biogas has the heating value of approximately 0.43 kg LP Gas*
- *1m^3 of Biogas approximates to about 1.25 hours of cooking*
- *The nominal daily energy output is equivalent to approximately 0.8 kg LP Gas*



Distributor contact details:

WARRANTY: The *BiogasPro* has a 3-year warranty. The complete installation when undertaken by AGAMA Biogas (Pty) Ltd or an accredited distributor is guaranteed for 1 year.

AGAMA Biogas (Pty) Ltd
Tel: 021-7013364 I Fax: 021-702 4920
Web: www.biogaspro.com
E-mail: info@biogaspro.com

BiogasPro agama

Figure 7-3: ABP6 product datasheet, page 2

Khanyisa PROJECTS

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	2	0,02		-0,04	2
2	Digester			0,09	-0,13	2
3	Pipe	1,5	0,02		-0,16	3,5
4	Soakaway			0	-0,16	3,5

Figure 7-4: Babunene site level estimation

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	3	0,02		-0,06	3
2	Digester			0,09	-0,15	3
3	Pipe	0,5	0,02		-0,16	3,5
4	Septic Tank			0,09	-0,25	3,5
5	Pipe	3	0,02		-0,31	6,5
6	Soakaway			0	-0,31	6,5

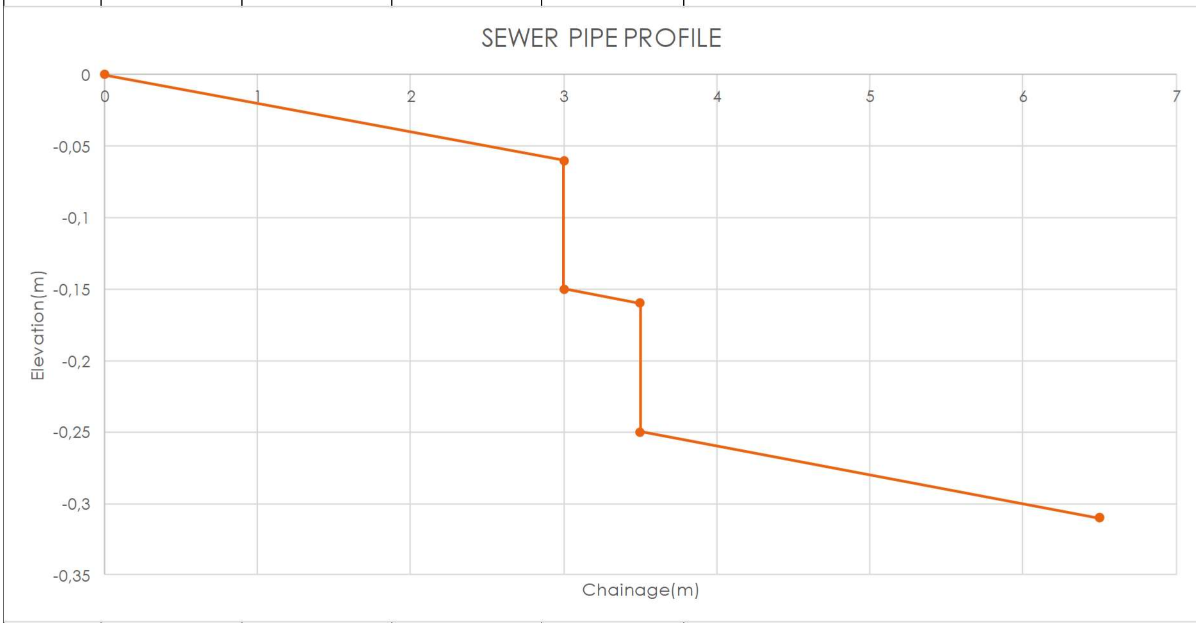


Figure 7-5: Ukuhlalanathi site level estimation

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	3,2	0,02		-0,064	3,2
2	Digester			0,09	-0,154	3,2
3	Pipe	1,5	0,02		-0,184	4,7
4	Septic Tank			0,09	-0,274	4,7
5	Pipe	1,5	0,02		-0,304	6,2
6	Soakaway			0,09	-0,394	6,2

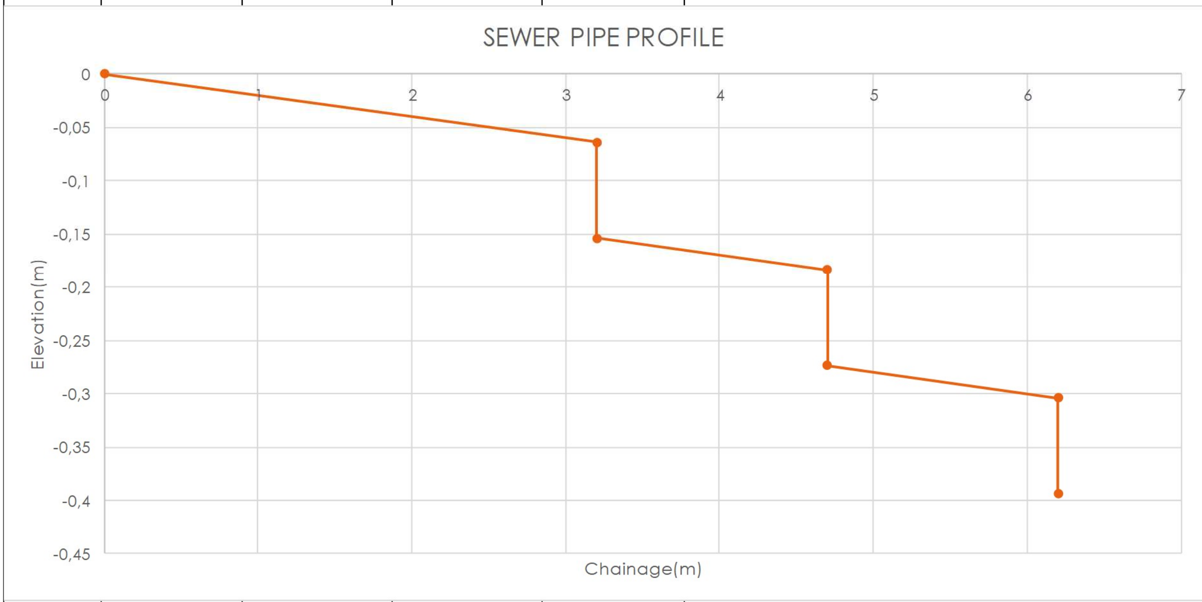


Figure 7-6: Vukuzenzele site level estimation

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	2	0,02		-0,04	2
2	Digester			0,09	-0,13	2
3	Pipe	1,5	0,02		-0,16	3,5
4	Septic Tank			0,09	-0,25	3,5
5	Pipe	6	0,02		-0,37	9,5
6	Soakaway			0,09	-0,46	9,5

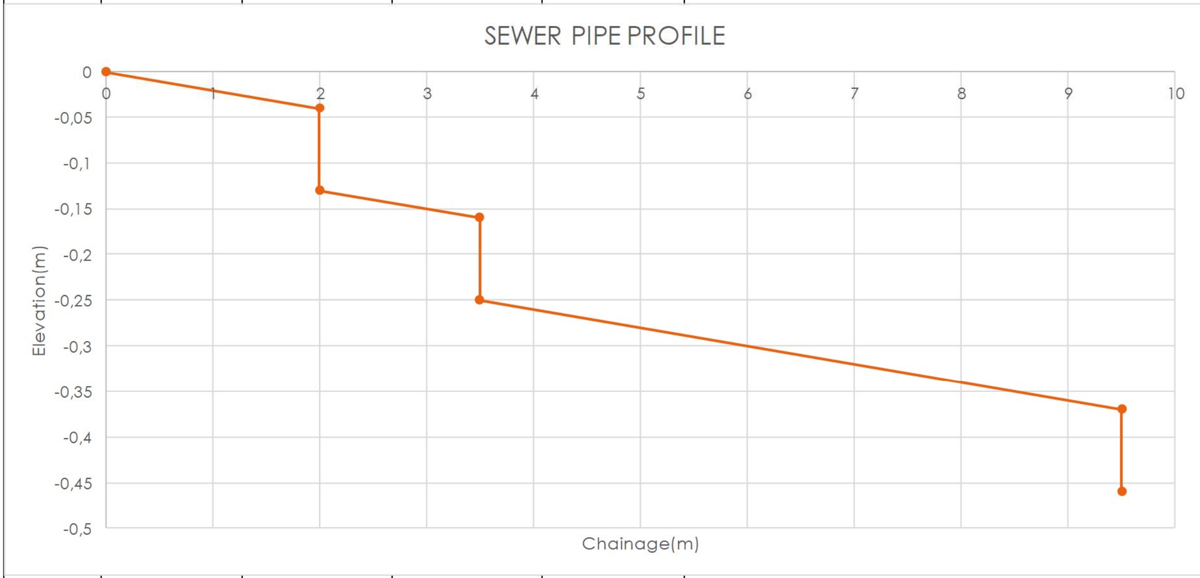


Figure 7-7: Siyaqhubekha site level estimation

Approximation of Pipe Level

Add Pipe

Add Structure

Clear entry

Point	Component	Pipe length	Slope	Drop	Invert level from reference (m)	Chainage(m)
Reference Level (meters):					0	0
1	Pipe	3,5	0,02		-0,07	3,5
2	Digester			0,09	-0,16	3,5
3	Pipe	1,2	0,02		-0,184	4,7
4	Soakaway			0,09	-0,274	4,7

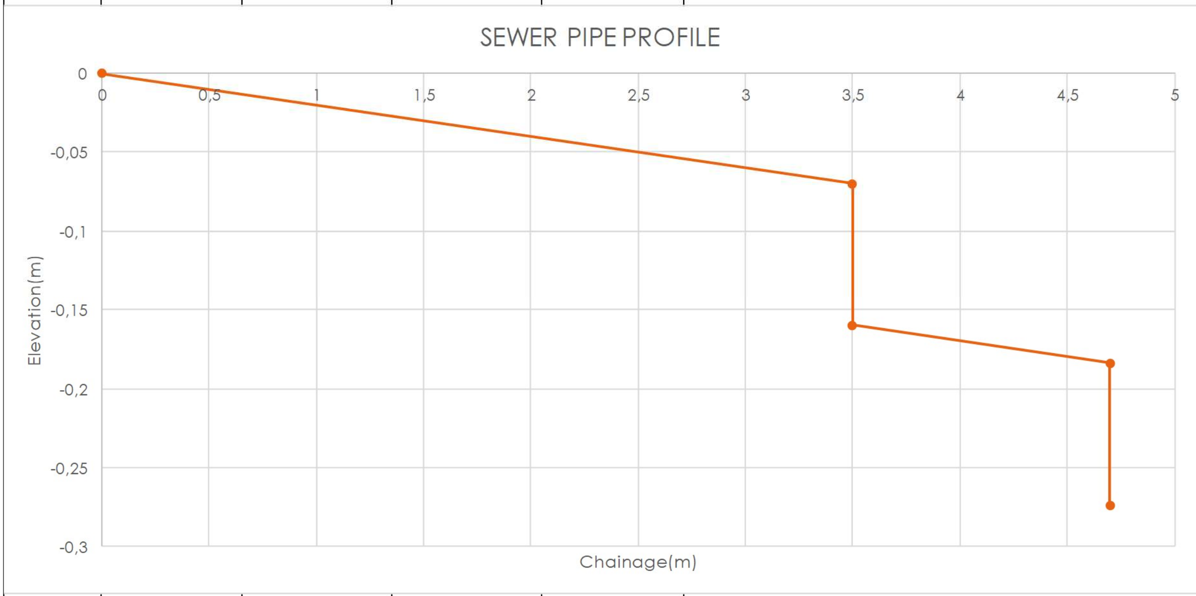


Figure 7-8: Sphumelele site level estimation

Table 7-2: Estimation of expected biogas yield ,solids and liquid input into digester

ECDC	Average Daily Attendance (Students)	Average Stool Weight (Kgs)	Average Urine Vol. (Litres)	Water Used Per Flush (Litres)	Water per Hand Wash (Litres)	Average Food Waste per day (Kgs)	Solids Flow Rate(Kg/day)	Liquid Flow Rate(Litres/day)	Biogas Yield (Human Excreta)	Biogas Yield (Food Waste)	Total Biogas	Available Cooking Hours	Required Cooking Hours
Ukuhlananthi	130	11,05	104	260	39	5	16,05	403	0,807	0,638	1,445	1,806	2
Vukuzenzele	37	3,145	29,6	74	11,1	1,423	4,568	114,7	0,229	0,181	0,411	0,514	0,569
Babunene	19	1,615	15,2	38	5,7	0,730	2,345	58,9	0,117	0,093	0,211	0,264	0,292
Sphumelele	50	4,25	40	100	15	1,923	6,173	155	0,310	0,245	0,555	0,694	0,769
Siyaqhubheka	100	8,5	80	200	30	3,846	12,346	310	0,620	0,491	1,111	1,389	1,538

Table 7-3: Maintenance and Troubleshooting Recommendations

Fault	Possible cause	Control measures	Remedy
(1) Structural tank defects causing water or gas leaks	The tank was purchased with a defect	Ensure appropriate sign–off of the tank delivery	Replace or repair the tank
	The tank was damaged during installation	Ensure certified installation.	Undertake certified defect repairs.
(2) No digestate overflowing from the *ABP6*	Debris in the inlet or inspection risers (e.g. plastic bag)	Correct operations and maintenance – regular checks for inorganic material.	Remove inorganic material
	Debris blocking the outlet (e.g. plastic bag).	Correct operations and maintenance – regular checks for inorganic material.	Remove inorganic material
	Leak in the structure	As per (1)	
	Blockage from overloading	Review loading rates on product datasheet	Ensure that design volumes are entering the system.

	Not enough water going into the system causing solidification within tank	Review loading rates on product datasheet	Add water to within design volumes
(3) Effluent backing up sewer pipes or overflowing out of inlet riser	Inorganic debris in inlet chute riser or excessive solid volumes in inlet riser.	Correct operations and maintenance – regular checks for inorganic material. Review loading rates on product datasheet	Remove debris and ensure correct volumes entering system.
	Solid or inorganic debris blocking outlet	Review loading rates on product datasheet	Ensure design volumes are entering the system
(4) Leak in the gas line	Incorrect installation	Ensure that the line is installed to specification, not close to vegetation growth and with no possibility of trapping condensation water. Ensure that components are operated and maintained correctly, weathered components replaced.	Contact specialist
	Damaged or broken pipes through vegetation growth into the joints.		
	Perished or corroded components		Regular inspections to replace damaged corroded or perished components.
Fault	**Possible cause**	**Control measures**	**Remedy**
(5) Blockage in gas line	Water trapped in pipe. This is usually evidenced by variable flame at the burner	Ensure that the gas line is not bent causing a "U" water trap in the line, ensure that water traps are checked and emptied regularly	Contact specialist
	Effluent backing up pipe	Ensure that scum or protein froth build up has not entered the pipe at the gas outlet.	
(6) Blockage or leak in the sewer line	Incorrect installation	Ensure that the line is installed to specification, not close to vegetation growth and with no possibility of trapping water. Ensure that components are operated and	Contact plumber

		maintained correctly, and weathered components replaced.	
	Damaged or broken pipes.		Regular inspections to replace damaged; broken or perished components.
	Incompatible material lodged in the line	User education. Put up toilet sign supplied.	Contact plumber
(7) Reduction in burning time	Severe cold weather, one can expect less gas production in the winter months. See product datasheet.	Review loading rates on product datasheet	Ensure only correct amount and type of raw material enters the digester at different times of the year
	Build up of in-organic material in the tank (sand, grit etc) causing the capacity to reduce	Review User Manual for avoiding inorganic materials being loaded into the ***ABP6***	
	Blockage, restriction, leak in gas pipe	Check for leaks, blockages.	Replace or repair components
(8) General malfunctioning of the burner	Burner parts dirty or corroded (food often falls into gas outlets, jets get blocked with carbon).	Clean (wire brush) appliance regularly	Clean appliance carefully and gently
	Using an incorrect appliance.	Use only a purpose-built biogas appliance.	Replace appliance if necessary.
(9) Irregular flame	Incorrect gas/air mixture.	Ensure correct control of the air/gas mixture on the appliance.	Confirm correct control of the appliance.
	Combustibility of gas insufficient.	Do a pH test to ensure an optimal environment for methane producing bacteria (pH = 6-8) exists within the digester.	Ensure correct environment for methane producing bacteria.
(10) Flame far from the burner.	Pressure too high.		Adjust gas valve.

	Deposition of carbon on the nozzle.		Clean nozzle.
	Air/gas ratio incorrect at appliance.		Adjust air/gas ratio on the burner
(11) Flickering Flame	Water in the pipe. See (5)	Check the gas pipeline/water trap for trapped water (if one exists)	Ensure that there is no water in the gas line and the water is removed from the water trap.
(12) No gas pressure at the appliance (but pressure in the reactor)	Stop valve(s) closed	Open stop valve(s)	Confirm all required valves are open and repair/replace components if necessary.
	Leak or blockage in the gas pipe line between the *ABP6* and the burner	Check for gas leaks or blockages throughout the gas line on leaking joints/couplers or on broken pipes or perished flexi hoses. Caused by sand or tree roots obstructing pipes, or water in the pipe (check for sufficient downhill gradient or the water trap)	Repair and replace as necessary
(13) Poisoning of the digester bacteria by toxic substance	Toxic substances (such as acid cleaner) entering the system through sewer or grey water pipes or through contaminated feedstock	Erect appropriate signage to prevent toxic substances entering the system. Use only bio-degradable detergents or pesticides. Check for diseased livestock.	Stop toxic substances entering the system, introduce fresh uncontaminated feedstock. If biology is completely dead the system should be pumped out and re-commissioned.
(14) Foul odour or change of colour of digestate	Incorrect pH – raised above 8 or below 6. The biological activity within the system is out of balance.	Ensure that only prescribed types and volumes of feedstock are used. Do pH tests monthly and check for contamination by toxic substances.	If the pH is below 6, add new and fresh feedstock. If problem persists contact a specialist.
(15) Not enough gas	Too little loading		Increase loading to designed input

	Incorrect feedstock		Change feedstock to designed feedstock. Check and adjust pH.
	Lack of liquids impeding hydraulic flow		Increase liquid input Ensure that water is not leaking out of the structure
	Too much liquid diluting the mixture		Decrease liquid input
	Gas leaking from tank or pipes	See above	
	Scum build-up in the reactor (gas cannot penetrate scum layer and reach the gas storage area).	See above	
(16) Scum formation within the tank	Incorrect raw material feedstock being used. Scum can form within the reactor, restricting or stopping the gas from bubbling up into the Gas Riser; instead, the gas will bubble out of the Inspection Riser	Ensure that only prescribed (wet, fresh and non-fibrous) raw material feedstock is used.	Contact a specialist to break up and remove scum Remove Gas Cap and performance maintenance

7.3. Appendix C: NLM Household Data

This appendix contains the budget that was used during the implementation of the digester systems, as well as the full maintenance data sheet.

Table 7-4: Original rural household digester implementation budget

1.Materials					
Element	**Unit**	**Qty**	**Grand Qty**	**Bill Rate**	**Bill**
Cement bags	no	16	416	R 85,00	R 35 360,00
Bricks 1100	no	1100	28600	R 3,00	R 85 800,00
Building Sand 2m3	m3	2	52	R 325,00	R 16 900,00
River sand 2m3	m3	2	52	R 325,00	R 16 900,00
Stone	m3	2	52	R 425,00	R 22 100,00
Lintels 800mm	no	2	52	R 85,00	R 4 420,00
8mm round bar 6m	no	5	130	R 85,00	R 11 050,00
Brickforce 75mm wide rolls	no	6	156	R 45,00	R 7 020,00
8 guage wire roll	no	1	26	R 150,00	R 3 900,00
concrete slabs for inlet and outlet	no	2	52	R 400,00	R 20 800,00
Fibre glass dome	no.	1	26	R 4 750,00	R 123 500,00
Gas pipe HDPE	m	12	312	R 50,00	R 15 600,00
Gas Fittings and stove	sum	1	26	R 1 500,00	R 39 000,00
Grey water materials	no.	12	312	R 35,00	R 10 920,00
Delivery Costs	km	275	6400	R 4,00	R 25 600,00
Tools per team (3 spades,3 shovels,wheel barrow,3 picks)	no.	4	4	R 2 000,00	R 8 000,00
Safety Equipment (overalls,shirts, boots- EPWP branded	no.	4	4	R 3 000,00	R 12 000,00

Signage EPWP estimate	sum				R 7 500,00
		SUBTOTAL	**SUBTOTAL**		**R 466 370,00**
2. Labour Cost 10.5 mths					
Element	**Unit**	**Qty**	**Qty**	**Bill Rate**	**Bill**
Foreman/technician	dys		210	R 400,00	R 84 000,00
Training Stipend	dys		40	R 100,00	R 4 000,00
skilled	dys		312	R 350,00	R 109 200,00
Semi Skilled	dys		0	R 275,00	R -
Unskilled	dys		936	R 120,00	R 112 320,00
Travel 800 km per month	km		8800	R 4,00	R 35 200,00
Std Reimbursables	mth				R 8 000,00
		SUBTOTAL	**SUBTOTAL**		**R 352 720,00**
3. Implementing Agent 12.5 mths					
Element	**Unit**	**Qty**	**Qty**	**Bill Rate**	**Bill**
Project Manager 30 hrs per mth	hrs		375	R 450,00	R 168 750,00
Skills Development/ QC - Technical Manager 12 dys pr mth	dys		150	R 1 700,00	R 255 000,00
Community Engagement 6 dys per mth	dys		75	R 900,00	R 67 500,00
Travel 2500km per month	km		31250	R 4,00	R 125 000,00
Std Reimbursables	mth				R 13 500,00
		SUBTOTAL	**SUBTOTAL**		**R 629 750,00**

5.Maintenance/ Aftercare /Evaluation (8 wks)					
Element	**Unit**	**Qty**	**Qty**	**Bill Rate**	**Bill**
Project Manager 8 hrs per wk	hrs		32	R 420,00	R 13 440,00
Technical Manager 3 days per wk	dys		24	R 1 700,00	R 40 800,00
Foreman/technician	dys		25	R 400,00	R 10 000,00
Travel 600 km per wk	km		4800	R 4,00	R 19 200,00
Std Reimbursables	mth				R 1 890,00
		SUBTOTAL	**SUBTOTAL**		**R 85 330,00**
				Total	**R 1 534 170,00**
				Contingencies 7%	**R 107 391,90**
				Grand Total	**R 1 641 561,90**
				VAT	**R 229 818,67**
				NETT TOTAL	**R 1 871 380,57**

Table 7-5: Maintenance done at Household Digesters

House names	**Feedstock**	**Maintenance done**
Zuma	• Works on black water	• Wall valve switch changed • Inlet cover is not secure • Changed manifold on stove • Condensation valve installed

		• Drilling of holes in plate burner • Leaking in the manifold of stove
M Ngcobo	• Uses cow dung, and grey water • Loads twice a week minimum	• Wall valve switch changed • Condensation valve installed • Handle in Inlet not present
Ndlovu	N/A	• Stove not present and gas line • Hardly ever been used
Mlangeni	• Uses cow dung and food waste • Last loaded on the 19th March • Loaded almost everyday	• Wall valve switch changed • Drilling of holes in plate burner • Condensation valve installed
Magwaza	• Uses cow dung and food waste • Loaded 5 days a week	• Stove was taken out one month ago • Hasn't been working several months before that • Torn pipe • Drilling of holes in plate burner • Condensation valve installed • Low quality gas
Phakathi	• Been a while since fed	• Serious blockages of plate burner holes, holes were drilled

	• Fed it every day before it broke	• Leak on pipe • Wall valve switch changed • Condensation valve installed • Replaced Gate valve
Ngiba	• Haven't loaded since 2016 • No cows	• Stove gone • Gas line and valves gone
Mngadi	• Last fed a week before visit	• Leaks on pipe • Valve on stove and wall valve switch is gone • Condensation valve installed • Drilling of holes in plate burner
P Ngcobo	• Last fed two years ago	• Pipe leaks • Low heat on stove • Condensation valve installed
J Ngcobo	N/A	• The old man does not remember the last time it work but says its been many years • No stove present • Valve on top of dome broken
Mthembu	• Hasn't been fed in a year • Uses cow dung	• Pipe leaks • Needs new valves at the dome

	• When it worked they fed it everyday	• Needs new wall valve switch and stove manifold
N Ngcobo	• Haven't fed digester in 3 weeks • Uses cow dung twice a day	• Pipe leaks • Condensation valve installed • Handle at the inlet not present
Shandu	N/A	• House is wrecked, no one was present
Hlongwa	• Hasn't worked for two years • No more cows	• Dome valve has been removed
Mbambo	• Hasn't worked in 3 years • Uses cow dung fed little to no water • Fed it once a day	• Change stove manifold • Condensation valve installed • Drilling of holes in plate burner
Mdima	Digester apparently has never worked	N/A
Ngidi	• Hasn't worked in 3 months • Uses cow dung	• Condensation valve installed • Drilling of holes in plate burner
Jali	• Last fed the week before site visit • Uses cow dung • Feed inside inlet was solid had little water	• Condensation valve installed • Drilling of holes in plate burner
Shangase	The digester did not worked since it was built since there was a settlement problem	N/A

	that occurred during construction	
Memela	• Hasn't worked since 2017 • Was fed once a day	• Fixed pipes • Condensation valve installed • Drilling of holes in plate burner
Gama	• Fed it once a day • Hasn't worked in a while • Put two dead full cows in the digester	• Fixed a number of pipe leaks • Put silicon around the stove switches • Condensation valve installed • Drilling of holes in plate burner
Nxumalo	• User is old and does not remember when digester broke however states it's been a while	• Replaced dome valve • Fixed three leaks • Condensation valve installed • Drilling of holes in plate burner • Wall valve switch changed and Q20 applied on the wall valve
B.G. Ngcobo	The dome has been burned	
Ngcobo	The pipe was torn during the construction of the new house and was completely removed from the dome to the stove	
Cibane	• Uses cow dung	

	• Fed it three days a week	

7.4. Appendix D: Characterisation Tests

This appendix contains the raw characterisation test data.

Table 7-6: RI7 Raw Data

Sample	Beaker Size	SG	Mass Sample	Volume Sample	Vol H2O	Total vol	Press N2	Press O2	nTotal	n O2 (B)	n N2 (B)	Δ Press	Press After	Press O2	n O2 (After)	mg 02	TS	DM	mg 02 /g DM	AVE	STD DEV	Average
Example	1	0,5	0,013	0,026	0	0,974	79,01	21,27	0,0405	0,00851	0,0316	2,0	99,3	20,286	0,00080	25,589	32,97	4,286	5,970	5,970	#DIV/0!	
Cow	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	81,0	20,3	-58,71	0,03192	1021,477	20,3	4,060	251,595	259,360	10,982	246,418
Cow	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	86	15,3	-63,71	0,03389	1084,531	20,3	4,060	267,125	243,829	32,945	
Cow	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	71	30,3	-48,71	0,02798	895,369	20,3	4,060	220,534	220,534		
Fecal Matter	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	93,0	8,3	-70,71	0,03665	1172,807	8,475	1,695	691,919	706,799	21,043	704,319
Fecal Matter	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	97	4,3	-74,71	0,03823	1223,250	8,475	1,695	721,679	710,519	15,783	
Fecal Matter	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	94	7,3	-71,71	0,03704	1185,418	8,475	1,695	699,359	699,359		
Food	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	71,0	30,3	-48,71	0,02798	895,369	23,93	4,787	187,043	168,602		175,627
Food	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	57,0	44,3	-34,71	0,02246	718,817	23,93	4,787	150,161	169,919		
Food	1	0,5	0,02	0,04	0	0,96	79,01	21,27	0,0399	0,00838	0,0311	72,0	29,3	-49,71	0,02837	907,980	23,93	4,787	189,677	189,677		

Table 7-7: COD Raw Data

Sample	**Volume**	**Control**	**Reading**			**Average**	**Result**
		Average	**1**	**2**	**3**	**value**	**mg/l**
Example	1	0,00325	0,065	0,064	0,065	0,065	**380,11**
01/08/2018							

Control	0		0,002	0,001	0,001	0,001	
KHP (standard)	1	0,00100	0,158	0,160	0,124	0,147	**905,66**
Cow.D	0,2	0,00100	0,592	0,554	0,598	0,581	**35916,00**
Fecal Matter	0,2	0,00100	2,959	3,009	3,329	3,099	**95867,61**
Food Waste	0,2	0,00100	3,120	3,500	3,167	3,262	**100921,96**
Inoculum	0,2	0,00100	0,814	1,053	0,234	0,700	**21640,87**
Inoculum Digestate	0,2	0,00100	0,026	0,058	0,138	0,074	**2258,99**
Food Waste Digestate	0,2	0,00100	0,36	0,331	0,333	0,341333	**42126,00**
Fecal Matter Digestate	0,2	0,00100	0,178	0,275	0,224	0,225667	**27809,00**
Cow Dung Digestate	0,2	0,00100	0,092	0,028	0,042	0,054	**9036,00**

Table 7-8:TS/VS Raw Data

Sample	TS (%)	VS (%)	MC (%)	TS (%)	VS (%)
	Average	Average		Std Dev	Std Dev
DGR 10	33,9498	62,3822	66,0502	4,7076	9,8422
Food W	23,9349	95,4632	76,0651	0,3193	0,4336
Cow.D	25,2532	88,5054	74,7468	0,1148	1,0377
Inoculum	3,2640	74,7716	96,7360	0,1072	0,8621
Fecal Matter	8,4750	83,0724	91,5250	0,6915	0,4090
Inoculum Digestate	2,085957	65,07873	97,91404	1,083439	26,28205
Fecal Matter Digestate	9,225676	70,07913	90,77432	6,855733	27,18397
Cow Dung Digestate	4,975014	76,80698	95,02499	0,263981	1,590897
Food Waste Digestate	3,311163	52,3589	96,68884	2,228288	3,781671

Table 7-9: BOD Raw Data

Before	IN	311,67	21,57	321	327	287	
	DG1	1798,33	264,32	1991	1907	1497	
	DG2	871,75	531,48	537	1665	620	665
After	CD	124,00	24,43	113	107	152	
	FW	204,00	130,78	127	355	130	
	HE	114,67	8,62	107	124	113	
	IN	105,03	17,31	124	90,1	101	

7.5. Appendix E: Gas Recordings

This appendix contains the daily biogas yield during the BMP Test as well as the carbon dioxide readings of both prototypes discussed in section 4.6

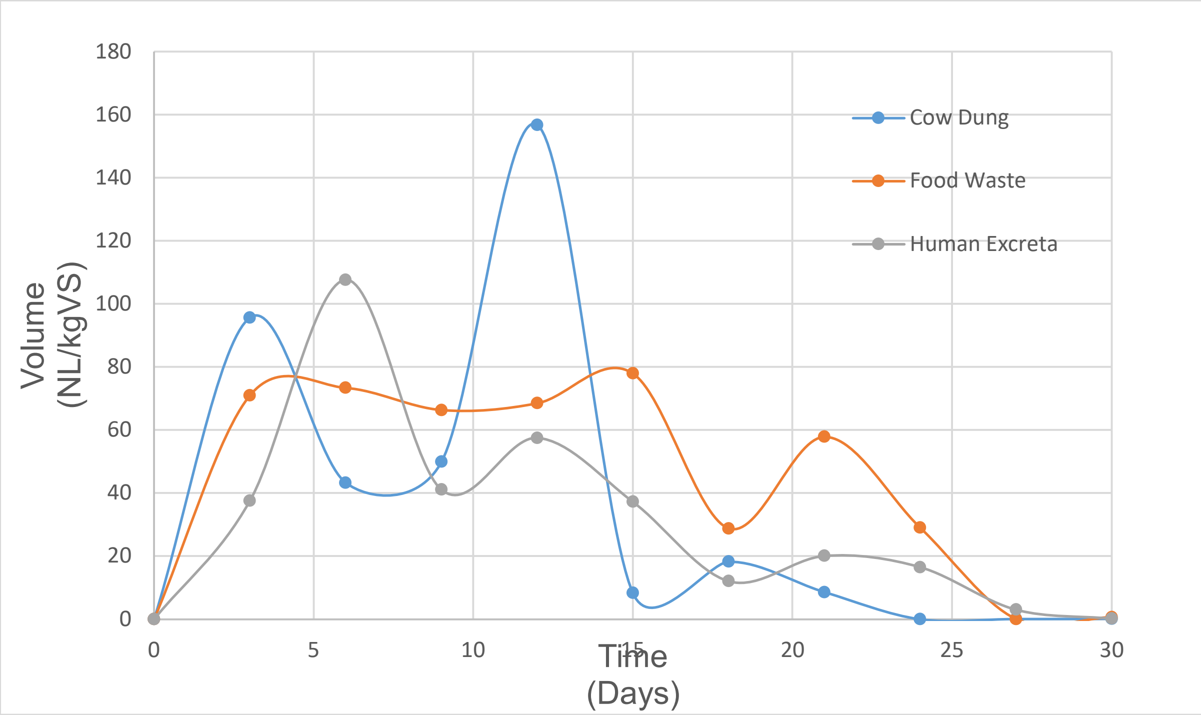


Figure 7-9: Daily biogas yield during BMP Test

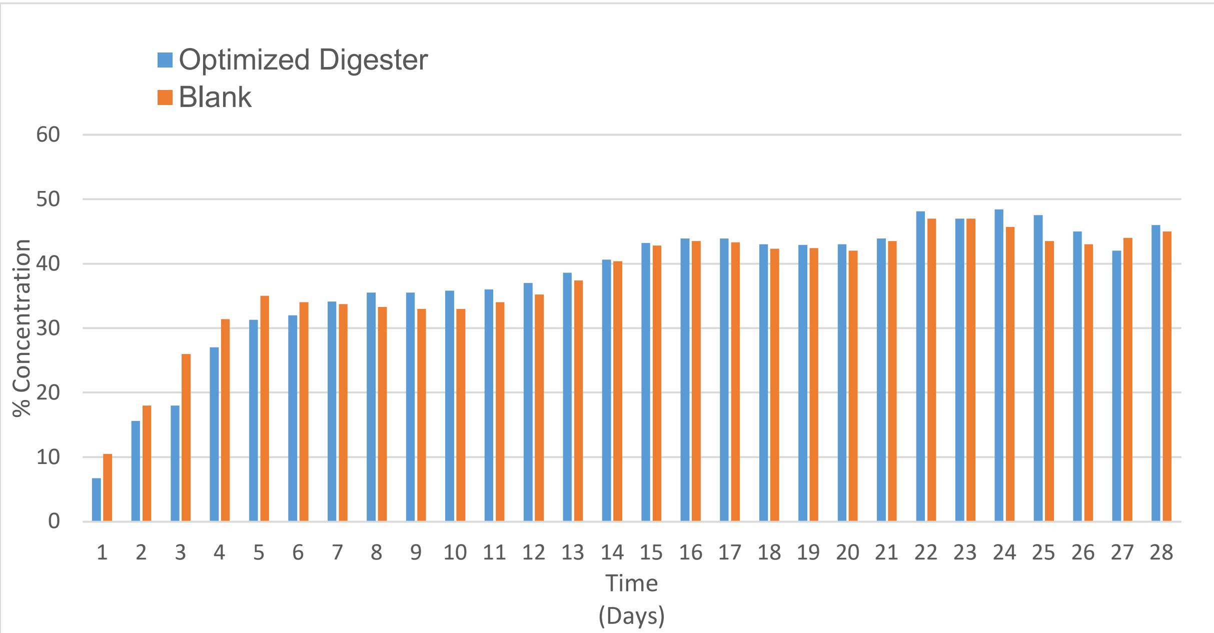


Figure 7-10: Carbon dioxide recordings of both prototypes