# Design, construction and performance evaluation of an agitated portable biogas digester under greenhouse-regulated temperature

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*Together in Excellence*

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# DEDICATION

This thesis is dedicated to my parents who indubitably supported the idea of me pursuing a Master of Science Degree above every other alternative that was at my disposal when I made the choice. Together with my siblings, they endured separation and deferred financial support from a dear son and brother for a cause well believed in.

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# ABSTRACT

Biogas yield in anaerobic digesters is negatively affected by low temperatures during cold seasons and nights, temperature fluctuations and inefficient agitation. Electrical heating and underground digester installations have been used to help minimise these effects but the high cost of electrical heating, infeasibility of underground installations in some terrains, inefficient agitation and difficult maintenance continue to be major set-backs to high biogas yields. In this study a 100 ℓ, agitated, portable carbon steel digester housed within a greenhouse, whose operation temperature is automatically maintained at an optimum of 35 ± 1 $^{o}$C by means of an ON/OFF electronic circuit for ventilation control through a suitably sized window and insulation offered by an air film trapped in-between a double layer of polyethylene plastic covering of the greenhouse, was designed. Cow dung from a dairy farm at the University of Fort Hare with total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and ammonia nitrogen content of 162348.67 mg/ℓ, 116543.98 mg/ℓ, 37 879 mg/ℓ and 128 - 235 mg/ℓ respectively was used for the performance evaluation of the digester. Analysis of the biogas produced starting from day 6 of the 31-day retention period showed a specific biogas yield of 0.036 $m^3/kgVS_{added}$ and a methane yield of 55%. The optimum pH maintained was 7.2 and the COD reduction achieved during the digestion period was 61%. This simple, easy to construct, inexpensive yet efficient design will lead to improved biogas yields and quality and faster dissemination of the biogas technology.

**Keywords:** biogas, digester, greenhouse, portable, agitation.

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# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND

A rapid increase in the emission of greenhouse gases (GHG) and fossil fuel prices, is the major motivator in the effort to maximize on utilization of renewable energy resources. The utilization of renewable energy is capable of significantly improving the standard of domestic life in remote regions that have no access to the grid (Panwar, Kaushik, & Kothari, 2011). Currently, renewable energy sources are contributing about 16.6% of the global energy and are expected to contribute more in the near future: 23.6% by 2020, 34.7% by 2030 and 47.7% by 2040 (Kralova & Sjöblom, 2010). The utilization of renewable energy is drawn back by challenges such as inconsistency in energy generation due to the fact that most of the renewable energy sources are climate dependent. This calls for adequate planning, robust design and use of efficient methods, if the advantages presented by the renewable energy are to be fully realised (Banos et al., 2011). Biomass is considered to be one of the most promising renewable energy sources. However, more research has to be done in order to prove the technical and economic viability of biomass energy (Banos et al., 2011). South Africa is suffering an energy crisis and is relying more on energy from fossil fuels. The country is contributing immensely to the wide-spread changes in climatic conditions (Cheng, Li, Mang, & Huba, 2013; Smith et al., 2013). To address these challenges, the government has come up with a strategy to move towards a green economy (DEA, 2016). The strategy involves expansion of the current 85% household electrification rate to 97% by 2025 (Smith et al., 2013). In doing so, renewable energy sources are expected to contribute both to grid and off-grid electrification. A national objective of 30% clean energy by 2025 has been set in an effort to realize the benefits of renewable energy sources (Benefits et al., 2014). Biogas, being a renewable source of energy, is one of the options under consideration.

The biogas technology is still in its infant stage and currently plays only a minor role in the overall bio-energy sector globally, although its global potential is quite impressive (Guo, Song, & Buhain, 2015). Anaerobic digestion technology for the production of bio-energy in form of biogas has been considered one of the highly energy efficient ways of biomass energy production. It is also very beneficial to the environment (Weiland, 2010). The possibility of production when needed, easy storage and compatibility with existing natural gas infrastructure, are some of the advantages that make biogas an attractive bio-energy source (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009). It was discovered that many small scale anaerobic digesters in developing countries fail due to inefficient design, poor maintenance, high capital cost of construction, operational problems and unavailability of construction materials (Nnamdi & Victor, 2015). If a larger fraction of the bio-waste generated globally would be anaerobically digested to produce biogas, the yield would displace about 25% of the current natural gas consumption and cover 6% of the global primary energy demand (WBA, 2013). This would mean a significant contribution of biogas to the target of 30% of the world's energy demand being formed by bio-energy by the year 2050 (Guo et al., 2015). The implication therefore is, the need for a significant increase in public awareness of the anaerobic digestion of bio-wastes and the availability of supporting structure and technology to enhance the growth of the biogas technology in the future.

## 1.2 PROBLEM STATEMENT

An efficient anaerobic digestion process operation, temperature control and substrate slurry agitation are key factors affecting biogas production. The fixed dome, floating drum and balloon type biogas digester designs have been exploited for biogas production over the years and have had many modifications done on them. It is however still not possible with most of these small-scale digester designs in current use to feasibly control the digestion operation temperature within a narrow optimum range as required by the anaerobic micro-organisms, which get upset by large temperature fluctuations. This leads to decreased process efficiency and biogas production. Electrical heating is not economical on the small-scale digesters and hence cannot be employed. Low temperatures experienced during cold nights and seasons are the major cause of the undesired adverse temperature fluctuations.

Another major limitation of the current digester designs is inefficient agitation which results in longer retention time, underutilization of digester volume due to formation of dead zones and consequently, decreased biogas production. In rocky and mountainous terrains, the installation of existing digester types is also not feasible and this implies that people living in such regions are not exploiting the benefits of biogas energy though they may be having the necessary substrates for biogas production. This limitation accounts for the unavailability of off-site renewable energy supplies necessary for people or organizations in transit, campers and those shifting from one location to another on a permanent basis.

From the reviewed literature there is no small-scale digester design with cheap and affordable efficient temperature control and agitation systems coupled together in a portable unit. The design of an automatically controlled temperature system, manually agitated portable biogas digester is therefore highly essential.

## 1.3 AIM AND OBJECTIVES

The aim of this research was to design, construct and evaluate the performance of an automated temperature control, agitated portable biogas digester.

To achieve the above aim, the following objectives were set:

i. To design and construct a digester vessel, agitator (anchor impeller) and a greenhouse.
ii. To determine the dairy cattle dung substrate properties such as total solids (TS), volatile solids (VS), pH, and chemical oxygen demand (COD) and feed the constructed digester.
iii. To measure the biogas production.
iv. To determine the biogas quality.

## 1.4 RESEARCH QUESTIONS

The following were the important questions answered in this research:

1. What factors affect methane production and how are these factors controlled to optimize the methane yield in the new design?
2. What are the limitations of the existing biogas digester designs?
3. How much biogas is produced and what is the biogas composition achieved in the new digester design?

## 1.5 SIGNIFICANCE OF STUDY

The research intended to bridge the knowledge gap that has led to unsatisfactory digester performance and failure in some cases. The energy demands of the community and other facilities can be met through the biogas technology. Increasing awareness and the attractiveness of the technology can result in faster dissemination of the technology. The national objective of South Africa and the global objective to increase the contribution of renewable energy sources and to make the sources constitute a more significant fraction of the total energy supply in the near future can thus be met.

## 1.6 ASSUMPTIONS

The study is based on the following assumptions:

- A well designed and constructed biogas digester produces a higher yield of biogas
- The composition of methane in biogas can be increased by proper temperature control and efficient agitation.
- A portable biogas digester is more convenient in remote regions

## 1.7 THESIS SYNOPSIS

This research documentation is divided into six (6) chapters as follows:
Chapter 1: This chapter gives the introduction, problem statement, aim and objectives of the research.

Chapter 2: This chapter gives the literature review on the biogas production processes, factors affecting biogas production, different types of biogas digesters and their limitations. The chapter also gives the theory of the mechanism of heat accumulation in a greenhouse and low pressure vessel construction for the digester design which was done in the research.

Chapter 3: This chapter gives the methodology followed in the design of the digester, its construction, and the determination of various substrate parameters before, during and after the feeding of the digester for performance evaluation.

Chapter 4: Here the results of the design and construction of the new digester are given.

Chapter 5: In this chapter, the biogas production rate, composition and substrate properties are collected and discussed.

Chapter 6: This chapter gives the summary of research findings, conclusions and recommendations.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter gives a background on biogas production, the factors affecting biogas production and the types of biogas digester designs that have been used since the introduction of the biogas technology. Starting with a brief description of biogas, the chapter outlines the environmental, social and economic advantages of the use of biogas. A strategy that has been put in place in order to enhance biogas production is outlined, followed by a detailed description and critical analyses of existing biogas digester designs, with their advantages and disadvantages being highlighted. To conclude the chapter, a recommendation of a new digester design, which is the thrust of this research, is given.

## 2.2 BACKGROUND ON BIOGAS

Biogas is a gas containing between 50-70% methane, 30–50% carbon dioxide, hydrogen sulphide, water vapor and other gases in small amounts and has a typical calorific value within the range of about 6 kWh/m$^3$ (Prasad, 2012), which makes it possible to provide enough energy to a five-member family for cooking. (Bond & Templeton, 2011). Biogas technology offers a unique set of benefits which include the improvement of user health, promotion of agricultural structural adjustment, increment of rural income, enhancement of the ecology of rural areas, optimization of the rural energy consumption structure and improvement of the quality of both rural life and agricultural products (Cheng et al., 2013). The gas has the attractive advantage of being a clean source of energy since it burns without leaving suit or ash (particulate matter) and is lighter than other gas fuels such as natural gas due to its shorter carbon chain length which also implies lower carbon dioxide production during combustion (Prasad, 2012). It enhances improved sanitation, reduced pathogens and disease transmission, reduced cost in energy production, reduced greenhouse emissions and reduced nitrous oxide (Bond & Templeton, 2011). Being smoke free, the gas also provides a healthier cooking environment (Kabir et al., 2013) as well as reduction in odors (Bruun et al., 2014), thus becoming a highly environmentally friendly energy source.

## 2.3 THE ANAEROBIC DIGESTION PROCESS

The anaerobic digestion process has four syntrophic stages: hydrolysis/liquefaction, acidogenesis, acetogenesis and methanogenesis (Divya, Gopinath, & Merlin Christy, 2015). The process commences with hydrolysis, the action of fermentative bacteria excreting enzymes such as amylase and protease to break down large and complex macromolecules to produce small, soluble organic compounds.

### 2.3.1 Hydrolysis

During hydrolysis, complex substrate molecules are broken down to simple soluble molecules which are more intimately accessible to bacterial action in the subsequent conversion steps. In this step insoluble complex organic matter is broken down into soluble constituents in order to allow their transport through microbial cell membranes (Madigan, Martinko, Dunlap, & Clark, 2008). Hydrolysis is achieved through the action of hydrolytic enzymes. In the first stage, fermentative bacteria convert cellulose, proteins and lipids into soluble sugars, amino acids and fatty acids respectively (Weiland, 2010). Proteases secreted by proteolytic microbes convert proteins into amino acids and xylanases produced by cellulytic and xylanolytic microbes hydrolyze cellulose and xylose (both complex carbohydrates) into glucose and xylem (both sugars) respectively while lipases that are created by lipolytic microbes convert lipids (fats and oils) into long-chain fatty acids and glycerol (Kangle, Kore, Kore, & Kulkarni, 2012). Figure 2.1 shows the anaerobic digestion process.

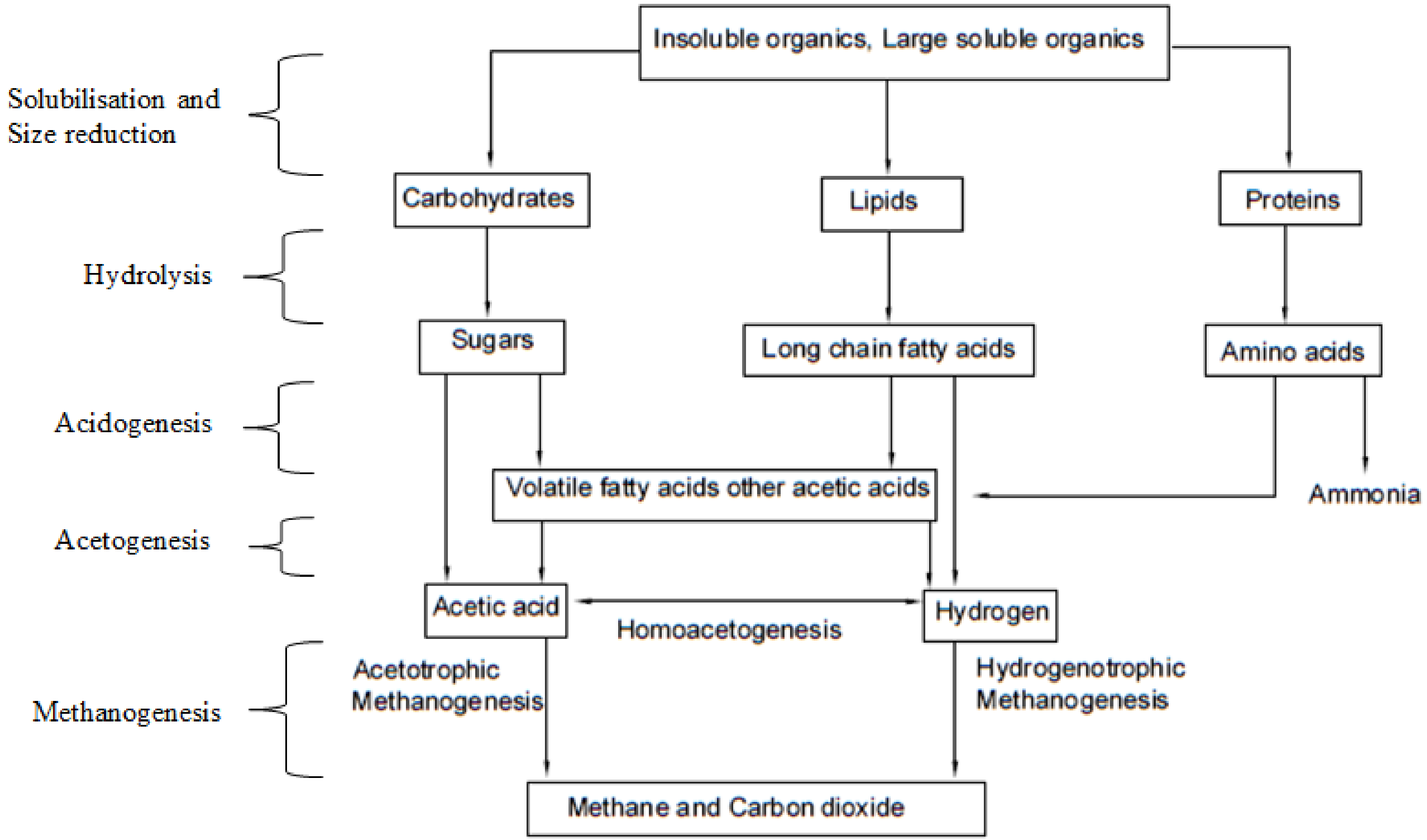

Figure 2.1: Pathways in anaerobic degradation (Adopted from Kangle, Kore and Kulkarni, 2012; Rajendran, Aslanzadeh & Taherzadeh, 2012 and Rouse, 2011)

### 2.3.2 Acidogenesis

Acidogenesis involves the conversion, by partial oxidation, of the sugars, organic acids such as amino acids and fatty acids produced during hydrolysis to hydrogen, acetate, carbon dioxide and volatile fatty acids (VFAs) such as propionic, n-butyric and iso-butyric acids, alcohol (ethanol) and lactic acid (Divya, Gopinath, & Merlin, 2014; Rajendran et al., 2012).

### 2.3.3 Acetogenesis

Acetogenesis is the conversion of the products of acidogenesis such as VFAs with more than two carbon atoms, alcohols and aromatic fatty acids into acetate and hydrogen by obligate hydrogen producing bacteria (Kangle et al., 2012). In this stage, acetogenic bacteria convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen (Guo, Song, & Buhain, 2015). The principal acids produced are acetic acid ($CH_3COOH$), propionic acid ($CH_3CH_2COOH$), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol ($C_2H_5OH$) (Divya et al., 2014). The products formed during acetogenesis are due to a number of different microbes such as syntrophobacter wolinii, a propionate decomposer and sytrophomonos wolfei, a butyrate decomposer. Other acid formers are clostridium spp, peptococcus anerobus, lactobacillus, and actinomyces (Kangle et al., 2012). While hydrogen-producing acetogenic bacteria produce acetate, $H_2$ and $CO_2$ from volatile fatty acids and alcohol, homoacetogenic bacteria create acetate from $CO_2$ and $H_2$ (Sterling, Lacey, Engler, & Ricke, 2001). But most of the acetate is created by hydrogen-producing acetogenic bacteria (Angelidaki, 2000).

### 2.3.4 Methanogenesis

The final step of the process is methanogenesis where acetic acid is converted to methane gas (Lemmer, Naegele, & Sondermann, 2013). A variety of methane-forming bacteria is necessary in the anaerobic digestion system since no single species can degrade all the available substrates. The methanogenic bacteria include methanobacterium, methanobacillus, methanococcus and methanosarcina (Kangle et al., 2012). Methanogens can also be divided into two groups namely the acetate consumers and the $H_2/CO_2$ consumers. Methanosarcina spp and methanothrix spp (also, methanosaeta) are considered to be important in anaerobic digestion (AD) both as acetate and

$H_2/CO_2$ consumers (Weiland, 2010). Approximately 70% of the methane is produced from acetate while the remaining 30% is produced from the reduction of carbon dioxide by hydrogen and other electron donors (Kangle et al., 2012). Methanogenesis is divided into two main routes, which are named depending on the substrate consumed by the methanogenic bacteria to produce the methane (Costa, Oliveira, & Alves, 2016) and (Smith et al., 2013):

1. Hydrogenotrophic methanogenesis: Hydrogen and carbon dioxide are converted into methane according to the reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + CO_2 \qquad [2.1]$$

2. Acetotrophic or acetoclastic methanogenesis: Methane is formed from the conversion of acetate through the reaction:

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad [2.2]$$

## 2.4 FACTORS AFFECTING BIOGAS PRODUCTION

The feasibility of anaerobic digestion systems is highly influenced by the substrate properties, digester operating conditions and digester design (Divya et al., 2015). An in-depth understanding of the complex set of biochemical and physicochemical reactions involved in anaerobic digestion is very essential for the successful design and operation of anaerobic biogas digesters. A proper design will not merely avoid digestion failure but improve the bio-methane fraction in the produced biogas and achieve efficient destruction of the organic content. Micro-organism growth rate is very crucial in the anaerobic digestion process for high biogas yield (Nayono, 2009). Cellulose, hemicelluloses and lignin are the major components of digester substrates that support the growth of anaerobic digestion microbes and the substrate physical and chemical characteristics such as moisture content, volatile solids, nutrient contents, particle size and biodegradability affect the anaerobic digestion process stability and biogas production (Divya et al., 2015). The activity of the various microbial groups in a substrate requires the strict adherence to specific ranges of operating parameters such as temperature, hydraulic retention time (HRT), pH, inhibitors, carbon to nitrogen ratio (C/N) ratio, volatile solids, total solids, organic loading rate, particle size, internal pressure and mixing as changes in any one of the parameter brings about flawed mineralization, a problem associated with the majority of biogas digesters (Divya et al., 2015). These digester operating parameters have to be controlled in order to help facilitate microbial activity and increase the anaerobic degradation efficiency of the system. The following section discusses the operating parameters in detail.

### 2.4.1 Volatile Solids (VS)

The Volatile Solids (VS) content in organic wastes is the fraction of the waste that would be obtained after complete combustion of the waste and subtracting the ash content from the total solids content. VS comprise the Biodegradable Volatile Solids (BVS) fraction and the Refractory Volatile Solids (RVS). Knowledge of the BVS fraction of substrate helps to better estimate the biodegradability of waste, generation of biogas, organic loading rate and C/N ratio. Wastes characterized by high VS and low non-biodegradable matter or RVS such as cow dung and pig manure produce burnable biogas at significantly less time (about 7 days) than other digester substrates and hence is best for AD treatment (Prasad, 2012).

### 2.4.2 Alkalinity

Alkalinity is crucial in pH control and enhances digester stability. It is by definition, the acid-neutralizing or buffering capacity of a digester (Rowse, 2011) and is described by the carbonate, bicarbonate and hydroxide content of the digester (Zhang, Su, Baeyens, & Tan, 2014). At neutral pH the carbon dioxide-bicarbonate system is primarily responsible for controlling alkalinity and thus the bicarbonate alkalinity is of great importance. Bicarbonate is also the main source of carbon for methane-forming bacteria. Alkalinity is mainly present in the form of bicarbonates in equilibrium with carbon dioxide gas at a given pH (Kangle et al., 2012). In anaerobic digestion alkalinity is also derived from the degradation of organic nitrogen containing compounds such as amino acids and proteins. During their degradation, amino groups are released which will further lead to the production of ammonia. Ammonia reacts with $CO_2$ yielding alkalinity in the form of ammonium bicarbonate. Additional alkalinity can be generated from the metabolism of the microorganisms in the anaerobic digester (Kangle et al., 2012). This type of alkalinity consists of the release of cations during the degradation of organic compounds.

### 2.4.3 pH Level

pH is the best indicator of future digester instability (Kangle et al., 2012). Acidogenesis and methanogenesis require different pH levels for optimal process control. In an anaerobic digestion system, optimum substrate degradation is achieved within a pH range of 5.5-8.5 since acidogenesis and acetogenesis are processes that lead to the accumulation of organic acids which drop the pH below 5, while methanogenesis causes an increase in pH over 8.5 due to the accumulation of ammonia (Divya et al., 2015). Acidogenic bacteria can perform well at a pH as low as 5 while methanogenic bacteria cannot survive at a pH below 6.2 (Mao, Feng, Wang, & Ren, 2015). Excessive generation of acid thus inhibits the growth of the acid sensitive methanogenic bacteria and hence the methanogenesis process. It has been determined that an optimum pH value for AD is 7 (Owner’s manual for the Energyweb DIY Biobag digester, 2014; Mao et al., 2015). The retention time of a substrate in the digester affects the pH value as initially, at the beginning of AD in the digester pH will decrease as organic matter undergoes acetogenesis but methanogens rapidly consume the formed acids raising pH again hence stabilizing digester performance. Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment.

### 2.4.4 Sulphate

Sulphates are reduced to sulfides biologically under anaerobic conditions, which may upset the biological process if the sulphide concentration exceeds 200 mg/l (Nayono, 2009). Some inhibitory compounds such as phthalate esters can also affect all major microbial groups in the digester in the same way while others may impair some specific microbial species (Ahring, 2003). Biological treatment of wastes containing toxic compounds constitutes an effective and cheap way for detoxifying the wastes (Angelidaki, Mogensen, & Ahring, 2000).

### 2.4.5 Ammonia

Ammonia within the digester is a result of protein degradation, influent carrying soluble ammonia and presence of urea (Weiland, 2010). There are two forms of ammonia depending on the pH of the system and these are the ammonium ion ($NH_4^+$) and the dissolved non-ionized form of ammonia ($NH_3$). It is generally accepted that it is the non-ionized form of ammonia that is responsible for AD inhibition (Weiland, 2010). The pH level has a significant effect on the level of ammonia inhibition as the pH value determines the degree of ionization (Sterling et al., 2001).

### 2.4.6 Temperature

Temperature is the principal environmental factor affecting biogas digester performance (Mata-Alvarez et al., 2014). It affects the physical and physico-chemical properties of compounds present in the digester and the kinetics and thermodynamics of biological processes (Kougias, Boe, & Angelidaki, 2013; Rowse, 2011). The two major temperature ranges providing optimum digestion conditions for the production of methane are the mesophilic and thermophilic ranges named after the micro-organisms that will be primarily active in that range. Mesophilic digestion takes place optimally between $30^oC$ - 38°C, or at ambient temperatures between $20^oC$ and 45°C while thermophilic digestion takes place optimally between $49^oC$ and $57^oC$ or at elevated temperatures up to 70°C (Zhang et al., 2014). The methane producing microbes are very sensitive to temperature fluctuations (Mukumba et al., 2015).

Biogas production and composition depend significantly on the ambient temperatures around the digester. When the biogas digester is not insulated there is an increase in temperature fluctuations as a result of heat transfer from the environment into the digester. Biogas production is highly affected by temperature fluctuations (Development & Auditorium, 2015). The methane producing microbes are very sensitive to these temperature fluctuations (Divya et al., 2015). Large temperature variations in the digester may lead to foam formation that will immensely affect total biogas yield (Divya et al., 2015). A stable operating temperature is very important for AD and changes in temperature of less than 0.5˚C/day are recommended (Rowse, 2011) in thermophilic digestion since greater deviations have adverse effects on biogas production (Prasad, 2012).

Temperature fluctuations depend on the quality and quantity of waste used, geometry of the digester, wall and floor thickness of the biogas digester and ambient temperatures of that location (Mukumba et al., 2015).

In designing biogas digesters, it is essential to know the thermal gradient between the digester internal and ambient conditions and the total heat exchange through the digester wall so as to come up with the suitable insulating material. However, a biogas designer should determine the best solution within the constraints of cost and material availability (Mukumba et al., 2015). Insulating the digester can minimize the fluctuations. Sawdust has been used as insulating material because of its low thermal conductivity of 0.08 W/ (m.K). Biogas production increases with increase in temperature but it has been empirically noted that the mesophilic temperature range gives the best biogas production when cow, chicken and pig manures are used (Prasad, 2012). Unheated plants and those without insulation do not work satisfactorily well when the mean temperature falls below 15 °C (Bond & Templeton, 2011).

### 2.4.7 Nutrients

Metals such as nickel, cobalt, molybdenum and iron are essential for optimal bacterial growth and to support enzymatic activities, chemical reactions and co-precipitation during the anaerobic digestion process and hence boost methane production (Mao et al., 2015). Trace metals play an important role in stimulating methanogenic activity. Selenium, molybdenum, manganese, aluminum and boron can be necessary additional components in a substrate (Kangle et al., 2012). Addition of easily degradable matter in the form of VFA improves the general behavior of the process due to an increased amount and activity of VFA degraders (Pind, Angelidaki, & Ahring, 2003).

### 2.4.8 Total solids content (TS)

Total solids (TS) is the fraction of solids in a substrate which is obtained after the complete removal of moisture through heating at a temperature of 105$^{o}$C for 24 hours. Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS) about 15% to 20% and high solids (HS) processes range from 22% to 40% (Kangle et al., 2012).

### 2.4.9 Organic loading rate (OLR)

The organic loading rate (OLR) is the organic matter flowing into the digester per time expressed as mass of organic matter over digester volume over time. It is the mass of volatile solids added each day per reactor volume or the amount of Biochemical Oxygen Demand (BOD) or Chemical Oxygen Demand (COD) applied to the reactor volume per day. Typical values of OLR range between 0.5 and 3 kg VS/m$^3$/d (Kangle et al., 2012). Organic loading gives a measure of the biological conversion capacity of the AD system. Over feeding the digester system above its OLR capacity results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry which decrease the pH in the reactor and can lead to reactor souring, or failure. It is therefore very important that the design of organic loading rate be conservative (Rowse, 2011).

### 2.4.10 Retention time

Hydraulic Retention Time (HRT) is the time that the fluid element of the feed remains in the digester or the average amount of time one reactor volume of actively digesting sludge stays within the digester while the solids retention time (SRT) is the residence time of the bacteria (solids) in the digester (Rowse, 2011). It is important to design reactors for sufficient retention times so that volatile solids destruction can take place to completion. Increasing SRT stabilizes the digestion process, lowers the amount of sludge produced and increases the extent the reactions involved in anaerobic digestion go to completion hence increasing biogas production.

A too short SRT results in organism washout and a too long SRT makes the system nutrient-deficient (Li et al., 2014). The optimum retention time for the completion of a given AD system depends on the technology used, process temperature and substrate composition, for instance, the retention time for wastes treated in a mesophilic digester ranges from 10 to 40 days while the retention times required for digesters operated in the thermophilic range are lower (Rajendran et al., 2012). A high solids reactor operating in the thermophilic range has a retention time of about 14 days. Given the relatively long generation time of methanogens, SRT should be over 12 days in order to avoid microbial washout (Weiland, 2010). Hydraulic retention time is important to reactor operation and design because it defines the length of time the substrate will be in contact with the biomass within the reactor. Methanogenesis is the rate-limiting step in most cases (Rowse, 2011).

### 2.4.11 Mixing

The purpose of mixing or agitation of substrate in a digester is to blend the fresh material with the digestate containing microbes (Mao et al., 2015). Mixing also prevents scum formation, maintains a chemically and physically uniform slurry and enhances the rapid dispersion of metabolic wastes produced during substrate digestion that could otherwise inhibit methane production, quickly disperses any toxic material entering the tank hence minimizing toxicity, prevents grit deposition and avoids temperature gradients within the digester. Excessive, disproportionate mixing can however interrupt the contact of organisms to the substrate and decreases biogas production hence mixing can however disrupt the microbes hence slow, occasional and harmonious mixing of the slurry in a digester which increases biogas production is preferred (Prasad, 2012). The type of mixing equipment, rate and amount of mixing varies with the type of reactor and the solids content in the digester. Agitation is also responsible for efficient enzyme activity (Divya et al., 2015).

### 2.4.12 Digester internal pressure

The pressure build-up within a digester is another predicted parameter that causes gas reduction and system exhaustion (Divya et al., 2015).

## 2.5 STRATEGY TO IMPROVE BIOGAS PRODUCTION

A strategy comprising four aspects for enhancing biogas production has been drafted. The aspects are briefly described below according to (Divya et al., 2015):

### 2.5.1 Biomass utilisation

This aspect focuses on the availability, and physico-chemical properties of substrates for anaerobic digestion to produce biogas. It includes research on co-digestion of several different substrates and substrate pretreatment.

### 2.5.2 Microbial treatment

The aspect deals with an understanding of the microbial growth kinetics and the genetic modification of bacteria.

### 2.5.3 Enzyme addition

In this aspect the focus is on enzyme activity, stability and optimisation.

### 2.5.4 Digester designs (Process optimisation)

This aspect focuses on bringing about improved digester designs expected to improve bio-methane production by giving attention to the mode of digester operation and digester operating parameters such as pH, temperature, C/N ratio, loading rate, TS and HRT.

## 2.6 BIOGAS DIGESTERS

A biogas digester is an airtight enclosed container designed to enhance the anaerobic digestion of biodegradable waste such as animal manure, domestic wastes, black water or sludge and the collection of the produced biogas (Spuhler, 2014). Biogas digesters are technical facilities in which the anaerobic degradation of organic compounds to produce biogas takes place (Raven & Gregersen, 2007). They have been used over the years to facilitate the production of biogas. Many improved biogas digester designs have been introduced and implemented in the world and currently, over 30 million digesters are in operation across the globe (Klavon & Lansing, 2010).

The biogas digester technology potential is however not being fully exploited due to inefficient or a lack of temperature control, the absence of, or inefficiency in agitation, gas leakages, unavailability of affordable materials for construction and construction expertise associated with the existing biogas digester designs (Bruun et al., 2014, Rajendran et al., 2012). There are about 700 digester installations done in South Africa since the introduction of the biogas technology in the country in 1957 by John Fry (Town, 2015). For some country rich in biomass deposits like South Africa this is an unexpected figure as compared to other countries like China with 17 million and India with 12 million installations (Town, 2015), and this indicates the need for a closer look at the effectiveness and attractiveness of the technology in the country.

Designs which deliver lower cost, improved robustness, functionality, ease of construction, operation and maintenance would aid the market penetration of biogas plants. Furthermore, to move beyond a dependence on livestock manure there is a need for small-scale bioreactors which efficiently digest available substrates in both rural and urban situations. On a domestic level these include kitchen waste, human excreta, weeds and crop residues (Bond & Templeton, 2011). This research falls under the fourth aspect of the strategy to enhance biogas production outlined above and it gives a summary of the different biogas digester designs installed in the world and particularly in South Africa ranging from the household, medium to the large scale.

## 2.7 BIOGAS DIGESTER CLASSIFICATION

Biogas digesters can be classified using different methods as follows:

### 2.7.1 Solids retention time (SRT) control

a) Passive systems: Biogas recovery is added to an existing waste treatment facility and there is little control of the anaerobic digestion process.

b) Low rate systems: Manure waste flowing through (into and out of) the digester is the main source of methane-forming microorganisms and it only leaves the digester when the designed retention time lapses i.e. the solids retention time (SRT) is equal to the hydraulic retention time (HRT).

c) High rate systems: Methane-forming microorganisms are trapped and retained in the digester to increase biogas production efficiency in the biodegradable material being fed into the digester (Hamilton, 2014).

### 2.7.2 Feed method

a) Batch digesters which are filled and then emptied completely after a fixed retention time when the reaction has come to completion.

b) Continuous plants which are fed and emptied continuously. They empty automatically through the overflow whenever new material is filled in.

c) Semi-batch plants where the reaction does not go to completion before additional substrate is added.

### 2.7.3 Biogas digester designs

a) Fixed-dome: The Chinese fixed-dome type is the most common (Angela Hojnacki, 2011). Models of the fixed-dome digester such as the Janta, Deenbandhu, CARMATEC model, AKUT fixed dome and AKUT Maendaleo have been designed (Angela Hojnacki, 2011).
b) Floating-drum type: This type includes the KVIC, Pragati, Ganesh, BORDA and ARTI models (Angela Hojnacki, 2011).
c) Polyethylene tube digester: A polythene tube/bag plastic (cheap) placed underground out of the outside environmental influence to produce biogas. It is also known as the PVC bio-bag digester.
d) Balloon type digester
e) Plastic roto moulded digesters
f) In-situ cast concrete digester (Puxin)

### 2.7.4 Biogas digester scale

a) Domestic or rural digesters (small-scale)
b) Medium-scale or large-scale commercial capacity
c) Agricultural/industrial digesters (large-scale)

### 2.7.5 Biogas digester construction

a) Onsite constructed digesters (OCDs)
b) Prefabricated biogas digesters (PBDs)

Prefabricated biogas digesters (PBDs) were designed to thwart the disadvantages of onsite constructed digesters (OCDs) which include long construction periods, relatively short lifetime, heavy construction material causing high transport costs and difficult repairing and maintenance once damaged (Cheng et al., 2013). The PBD types in use are the fiber-reinforced plastic (FRP) plastic soft (PS) and plastic hard (PH) digesters. PBDs can bear sufficient mechanical strength with good airtightness and long lifespan because their quality is determined and controlled during manufacture. OCDs and PBDs are compared in Table 2.1.

Table 2.1: Qualitative comparison between PBDs and OCDs (Cheng et al., 2013).

| **Item** | **FRP digester** | **PS digester** | **PH digester** | **Masonry digester** |
|---|---|---|---|---|
| **Cost** | High | Small | Normal | Normal |
| **Construction period** | Short | Short | Short | Very long |
| **Transportation** | Easy | Very easy | Easy | Impossible |
| **Maintenance** | Almost no | Almost no | Almost no | Frequent |
| **Mechanical property** | High | Weak | High | High |
| **Service life** | Long | Short | Long | Normal |
| **Water adsorption** | Low | Low | Low | High |
| **Tightness** | Good | Normal | Good | Normal |

Table 2.2 gives the advantages and disadvantages of PBDs.

Table 2.2: Advantages and disadvantages of PBDs (Cheng et al., 2014).

| **Category** | **Advantages** | **Disadvantages** |
|---|---|---|
| **FRP digester** | -Mature production process<br>-Uniform quality under industrial standards<br>-Good air tightness<br>-High gas production<br>-Fast heating up | -High cost of construction materials<br>-Floating where high underground water level persists<br>-Digester shape needs to be improved<br>-Secondary pollution after breakdown |
| **PS digester** | -Low production cost<br>-Good air tightness<br>-Fast heating up<br>-Easy transportation | -Easily pierced by sharp objects<br>-Aging of materials<br>-Extra pump required to transport gas<br>-Inconvenient feeding and discharge |
| **PH digester** | -Low production cost<br>-Good air tightness<br>-Fast heating up | -Easily damaged by blunt objects so stress intensity should be improved<br>-Floating where high underground water level persists<br>-Material is easily oxidized when exposed to air or buried in the earth |

## 2.8 EXISTING BIOGAS DIGESTER DESIGNS

In this section, the various digester designs that are in existence are described and explained and the strengths and shortcomings of each design are also given.

### 2.8.1 Small scale digesters

These are domestic, rural digesters installed for households or small facilities for direct gas usage rather than generation of electricity. They are the most common installations in South Africa and they find application in cooking, lighting and sanitation in the rural schools and villages. In this category are the In-situ cast concrete (Puxin), brick and motor fixed dome, plastic bag / biobag (BiogasSA), plastic roto moulded / PVC: BiogasPro (Agama) and Little Green Monster (Energyweb), and the Floating dome digesters (Munganga, 2013; Benefits et al., 2014). About 110 domestic digesters which include the fixed dome, balloon and PVC digesters by SANEDI and the University of Fort Hare in the Eastern Cape Province and 21 in the Kwazulu Natal province have been installed recently and are in use currently (Munganga, 2013). Their applications are cooking, lighting & sanitation in rural residential areas, schools and villages. The low rate digesters such as the Chinese fixed dome, Indian floating drum and balloon digesters have volumes between 2 and 10 $m^3$ and they produce around 0.5 $m^3$ of biogas per $m^3$ of digester volume (Bond & Templeton, 2011).

#### 2.8.1.1 Fixed dome digester

The brick and mortar fixed dome digester is made up of one unit which consists of the digester, gas storage dome and slurry displacement chamber built underground to avoid temperature fluctuations between daytime and night hours and to withstand the gas pressure to be exerted on the dome. While the underground digester is protected from low temperatures at night and during cold seasons, sunshine and warm seasons take longer to heat up the digester. No day/night fluctuations of temperature in the digester positively influence the bacteriological processes (GTZ, ISAT, 2007).

It is constructed using bricks, aggregate and cement-sand mortar. The construction of this digester design requires skilled masons since the digester is prone to cracking and hence gas leakages (Singh et al., 1997). The reactor has a constant volume and when gas is produced it displaces the slurry under its pressure into the expansion chamber. The digester is filled through the inlet pipe until the level reaches the bottom level of the expansion chamber. The difference between the levels of the slurry inside the digester and that in the expansion chamber is the gas pressure head responsible for the pressure of the gas (Rajendran et al., 2012). The slurry flows back into the reactor as the gas is removed from the reactor for use. The pressure build-up due to constant volume of the dome enhances the transport of biogas through pipes for use (Spuhler, 2014). Figure 2.2 shows a typical brick and mortar fixed dome digester.

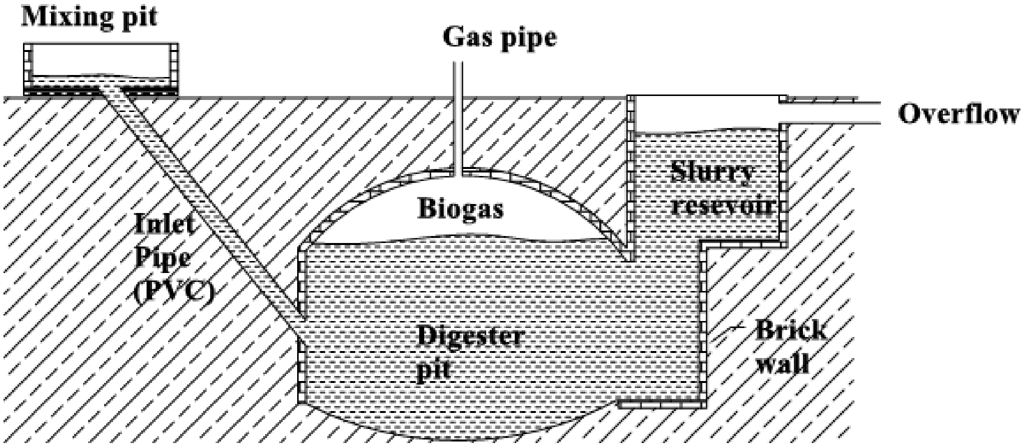

Figure 2.2: Brick and mortar fixed dome digester (Samer, 2012)

Depending on location, household membership, and the amount of substrate available per day, the sizes of these digesters vary. Advantages of the brick and mortar fixed dome digester are that it has low initial and maintenance costs as there are neither moving nor metallic parts prone to rust (Saleh, n.d.). The materials for construction are readily available in the rural areas making this digester design affordable for the residents there. The design however has the several disadvantages: It supplies gas at variable pressure since the gas storage dome is of constant volume and once the gas begins to be used there is no means provided to maintain its flow at a constant pressure. This implies that the gas pressure is less efficient to run any type of biogas equipment such as gas water heaters, lights and generators. Fixed dome plants produce just as much gas as floating-drum plants, if they are gas-tight. However, utilization of the gas is less effective as the gas pressure fluctuates substantially (GTZ, ISAT, 2007). The material used for its construction is prone to cracking therefore the construction requires a very high level of skilled labour which is not readily available in many cases and also time consuming. Repair of the digester in the event of leakages has paused a great challenge to many users of this digester design and history has shown that this aspect has been the biggest cause of failure of fixed dome digesters due to the development of cracks as the cement cures and/or as a result of differential stabilization of the structure on the ground. More than 50% of this type of digester has a functional life span of not more than 3 years (Cheng et al., 2014). The need for excavation which makes the design unsuitable in rocky terrains, observed inefficient agitation, possibility of solid deposition due to inefficient agitation, difficult maintenance and cleaning are other limitations of the brick and mortar Fixed dome digester design. There are also no rusting steel parts and hence a long life of the plant (20 years or more) can be expected (GTZ, ISAT, 2007). The operation is not understood by the household, since the amount of gas present in the digester cannot be seen (Rowse, 2011).

Fixed dome digester designs include:

- C**hinese fixed-dome plant** is the archetype of all fixed dome plants. Several million have been constructed in China. The digester consists of a cylinder with round bottom and top.
- **Janata model** was the first fixed-dome design in India, as a response to the Chinese fixed dome plant. It is not constructed anymore. The mode of construction lead to cracks in the gasholder - very few of these plant had been gas-tight.
- **Deenbandhu,** the successor of the Janata plant in India, with improved design, was more crack-proof and consumed less building material than the Janata plant. with a hemisphere digester
- **CAMARTEC model** has a simplified structure of a hemispherical dome shell based on a rigid foundation ring only and a calculated joint of fraction, the so-called weak / strong ring. It was developed in the late 80s in Tanzania (GTZ, ISAT, 2007).

#### 2.8.1.2 Floating drum digester

In a floating drum reactor, an underground digester pit is covered by an inverted steel gasholder which moves up and down as gas is generated and withdrawn respectively. The gasholder floats either directly on the fermentation slurry or in a water jacket. A guiding frame prevents the gas drum from tilting and if the drum floats in a water jacket, it cannot get stuck, even in substrate with high solid content. Floating drum digesters have the advantage that the gas pressure remains constant (Saleh, n.d.) as it depends on the weight of the gasholder which applies the pressure needed for the gas to flow through the pipeline to where it will be used. The construction is relatively easy and construction errors do not lead to major problems in the functioning and gas yield of the digester. It is also easy to determine the volume of the stored gas and to the operation of the digester is simple. However, the material costs of the steel drum are very high and all the steel parts are susceptible to corrosion which implies the need for regular maintenance and ultimately a short lifespan of 8 years (Fulford, 1988; GTZ, 2007). Figure 2.3 shows a floating drum digester.

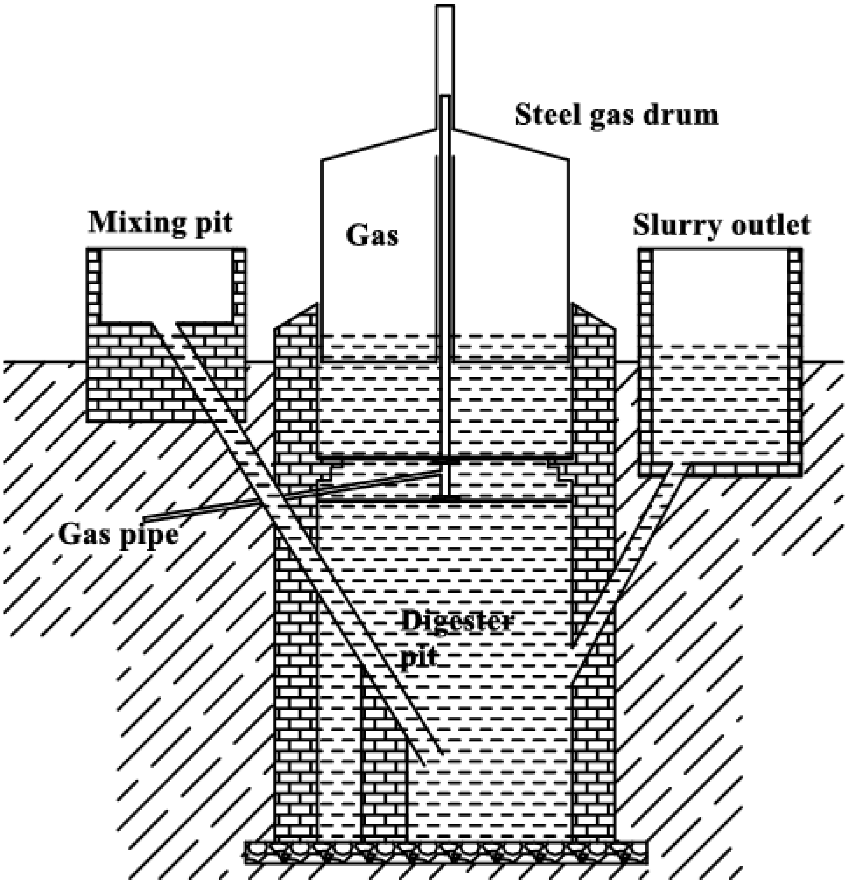

Figure 2.3: Floating drum digester (Samer, 2012)

The life-time of the drum is short (up to 15 years in tropical and coastal regions) (Rowse, 2011). If fibrous substrates are used, the gas-holder sticks to the floating scum (GTZ, ISAT, 2007). Floating-drums made of glass-fiber reinforced plastic and high-density polyethylene have been used successfully but the construction costs are higher compared to using steel.

If there are fibrous materials in the slurry as is the case most times, they will block the movement of digester gasholder hence their accumulation should be avoided (Rajendran et al., 2012). This has been observed to farther reduce the efficiency of the slurry agitation that would otherwise be achieved by the gasholder. This design has also been observed to be inefficient in agitating the slurry to avoid deposition of solids and to expose the substrate to microorganisms though it efficiently prevents scum formation on the slurry surface. The sliding mechanism requires relatively specialized design and construction is costly and requires consistent maintenance. The use of insulation materials such as straw to avoid temperature fluctuations as is done in some designs such as the fixed dome, is not possible with this design and more heat is inevitably lost around the circumference of the gasholder where it floats in the slurry or water. The digester is however gas leak proof (Singh et al., 1997).

#### 2.8.1.3 Biobag digester

Biobag digesters, also known as balloon digesters were developed to solve problems experienced with brick-and-metal digesters (Cheng et al., 2014). The Biobag is made of durable, flexible, reinforced and extremely strong PVC material that will provide long term, maintenance free operations for up to 15 years (OMEBD, 2014). The Biobag digester is simple to install and requires limited training and skills making it ideal for rural communities to install themselves. This digester has two waterproof manholes (inlet and outlet) which are at different depths to ensure flow of substrate under gravitation. The Biobag is in the form of a cylinder and the bottom of the excavation is left rounded so that the biobag maintains its rounded shape which also helps the flow of the contents from inlet through to the outlet. The slurry level within the Biobag is maintained at two thirds the diameter of the biobag. This level is controlled by the level of the outlet pipe in the outlet manhole. The remaining space in the Biobag is for biogas storage. A Biobag digester is operated within the mesophilic temperature range and can be insulated by covering the Biobag using straw or other insulating material such as polystyrene. The easiest way to raise the temperature would be to heat the slurry in the inlet manhole. Once the substrate has been fed into the inlet of the digester, it is important to top up with water to ensure that the level of the slurry in the inlet manhole is above the inlet pipe so as to avoid the entrance of oxygen which inhibits the anaerobic reaction (OMEBD, 2014). A pressure pump to supply the gas at the desired pressure or weights placed on top of the Biobag to provide enough pressure to push the gas from the Biobag to the appliances are used. A pressure relief mechanism is also incorporated where gas bubbles into water and out into the atmosphere. In cases where there is need for desulphurization a small desulphurization unit is added and there is also a moisture trap point to remove condensed vapor from the gas. Figure 2.4 shows a Biobag digester.

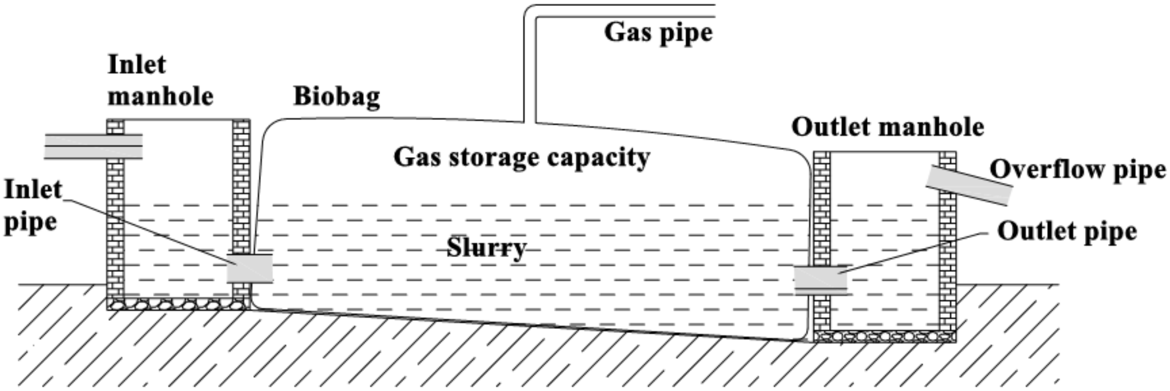

Figure 2.4: Biobag digester (OMEBD, 2014)

Advantages of the biobag digester include standardized prefabrication at low cost, shallow installation suitable for use in areas with a high groundwater table, high digester temperatures in warm climates, uncomplicated cleaning, emptying and maintenance and ability to digest efficiently difficult substrates like water hyacinths.

Despite the fact that the biobag digester design is easy to install and has several accessories of biogas upgrading and safety features, it has several disadvantages which include the fact that the plastic material used is prone to damage, expensive and is directly affected by change in ambient temperatures. The gas produced in the Biobag is at a low pressure hence the need for a pump. Above these problems it was farther observed in the biobag installations done in South Africa that loose clamping of the plastic onto inlet and outlet pipes due to limited working space, gas pipe connection to the plastic that is not air tight due to disturbances during inflating and deflating and the escape of gas through the inlet and outlet pipes as a result of them not being covered under the slurry are common problems. Many stakeholders lack the appreciation of the efficient operation of the digesters which need constant monitoring of the slurry level above the inlet pipe to avoid the escape of biogas. Those that have been enlightened on the need to maintain the appropriate slurry level find it difficult to do due to the fact that the digesters are not sized properly in accordance with family sizes as they should but rather they are too big for the stakeholders to keep filling in and maintaining slurry level above the inlet pipe. Another disadvantage realized is that the digesters are not covered and children sometimes throw some stones and twigs inside thus damaging the plastic. The lack of agitation is another limitation of this design as there is a tendency of scum formation and clogging inside the digester thus potentially failing the system although semi-continuous feeding can reduce the chances of failure. The useful life-span of this digester design does not usually exceed 2-5 years (Rowse, 2011).

#### 2.8.1.4 AGET digester (10 $m^3$)

Africa green energy technologies (AGET), a private company in Cape Town, South Africa has designed a 10 $m^3$ underground digester which handles a daily substrate input amount of 120 kg to produce 8 $m^3$ of biogas. This can give 8 kW h of energy. The digester works together with a separate biobag which receives biogas collected from a digester. The biobag is lightweight, safe and environmentally friendly and connects to a number of appliances (e.g. stove, lamp and heaters). The biobag can also be placed indoors as it is very strong enough to withstand punching by sharp objects. The gas is scrubbed and compressed when it leaves the underground digester. AGET has carried out pilot projects in the Western Cape (Phillipi) and Eastern Cape (Fort Cox, Fort Hare, Melani Village) Provinces. This digester has the advantage over other underground digesters of a portable gas storage bag (biobag) which can be kept anywhere and the gas pumped at the required pressure through use of a gas pump. Figure 2.5 shows the AGET 10 $m^3$ biogas digester and biobag.

Figure 2.5: The AGET 10 $m^3$ digester and biobag

### 2.8.1.5 AGET portable digester (2.5 $m^3$)

This is a very small digester which processes between 5 and 8 kg of kitchen waste to produce 2 $m^3$ of gas on a daily basis. Figure 2.6 shows the AGET 2.5 $m^3$ portable digester.

Figure 2.6: The AGET 2.5 $m^3$ portable biogas digester

This digester eliminates the limitations of an underground digester and has the convenience of easy transportation. Biogas supply pressure can also be determined and controlled by aid of pressure gauge and pump. High biogas yields are achieved due to the integrated 12 W photovoltaic (PV) module which powers a gas pump. Before temporary storage in the biobag, the biogas goes through a small scrubbing unit which increases its energy value hence giving the design a significant advantage of other designs. The AGET 2.5 $m^3$ digester however has the disadvantage of inefficient agitation and a relatively high cost.

### 2.8.1.6 Masonry digesters

Masonry digesters do not necessarily need stable soils. It is sufficient to line the pit with a thin layer of cement (wire-mesh fixed to the pit wall and plastered) in order to prevent seepage. The edge of the pit is reinforced with a ring of masonry that also serves as anchorage for the gas-holder (Cheng et al., 2014). The gas-holder can be made of metal or plastic sheeting. If plastic sheeting is used, it must be attached to a wooden frame that extends down into the slurry and is anchored in place to counter its buoyancy. The requisite gas pressure is achieved by placing weights on the gas-holder. An overflow point in the peripheral wall serves as the slurry outlet. The advantages of this digester design include low cost of installation (as little as 20% of a floating-drum plant) and high potential for self-help approaches while the disadvantages include a short lifespan, serviceable only in suitable, impermeable types of soil above groundwater (Cheng et al. 2013).

#### 2.8.1.7 Ferro cement plants

The ferro-cement type of construction can be applied either as a self-supporting shell or an earth-pit lining. The vessel is usually cylindrical. Very small plants (volume under 6 $m^3$) can be prefabricated. As in the case of a fixed-dome plant, the ferro cement gasholder requires special sealing measures (proven reliability with cemented-on aluminium foil). The advantages of ferro cement digesters include low cost of construction, especially in comparison with the potentially high cost of masonry for alternative plants, mass production is possible and low material input and the disadvantages include substantial consumption of essentially good-quality cement, the need for workmanship to meet high quality standards, use of substantial amounts of expensive wire mesh, construction technique not yet adequately time-tested, special sealing measures for the gas-holder are necessary. (GTZ, ISAT, 2007).

#### 2.8.1.8 Plastic roto-mould digesters

In South Africa there are three types of plastic roto-mould digesters in common use currently.

***EZ-digester***

The EZ-digester is a portable, above ground floating dome type digester that is quick and simple to install. It has specifically been designed to be used by individual households for rural and urban community applications. This digester is manufactured from heavy duty rotor molded plastic and has a life expectancy of over 10 years (Benefits, n.d.). Figure 2.7 shows the EZ – digester.

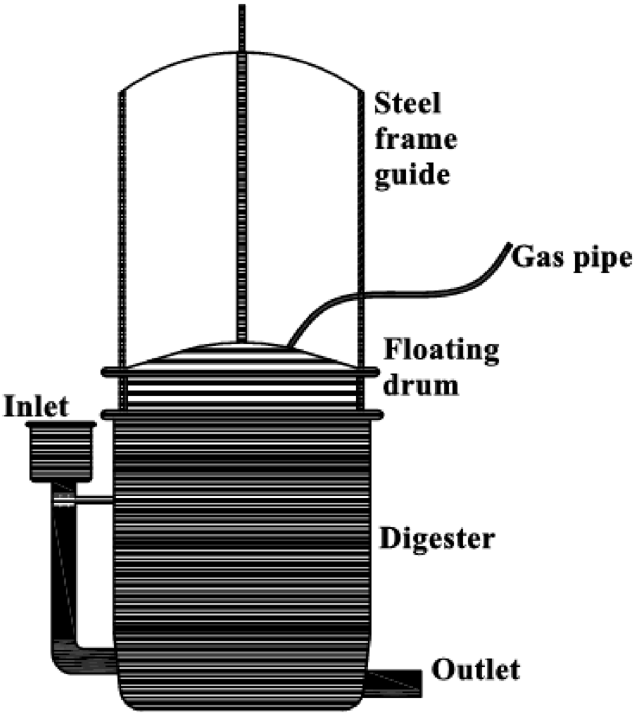

Figure 2.7: EZ-digester (Benefits, n.d.)

Being made out of plastic, the digester cannot be affected by corrosion as is the case in the traditional floating dome digester which has a metallic gasholder. This digester is also portable and above ground, factors which make it applicable and feasible in any given location as there is no need for ground excavation. The design however has the limitation of inefficient agitation of the substrate which is a significant factor affecting biogas production. The only extent of agitation possible with this design is that achieved by the upward and downward motion of the gas holder and the inflow of new substrate feed which does not suffice for the maximum benefits of agitation to be realized. The other limitation is the absence of a temperature control mechanism since insulating is not suitable due to the constant movement of the gasholder. Heat gained by the slurry during the day is lost to the environment around the circumference of the gasholder dipping in the slurry. The drum can also clog into the slurry when scum forms hence the need for constant maintenance.

***Little green monster digester***

This digester design consists of a tank made of a robust yet light weight, UV stabilized polyethylene plastic material that cannot corrode. Figure 2.8 shows the Little green monster digester.

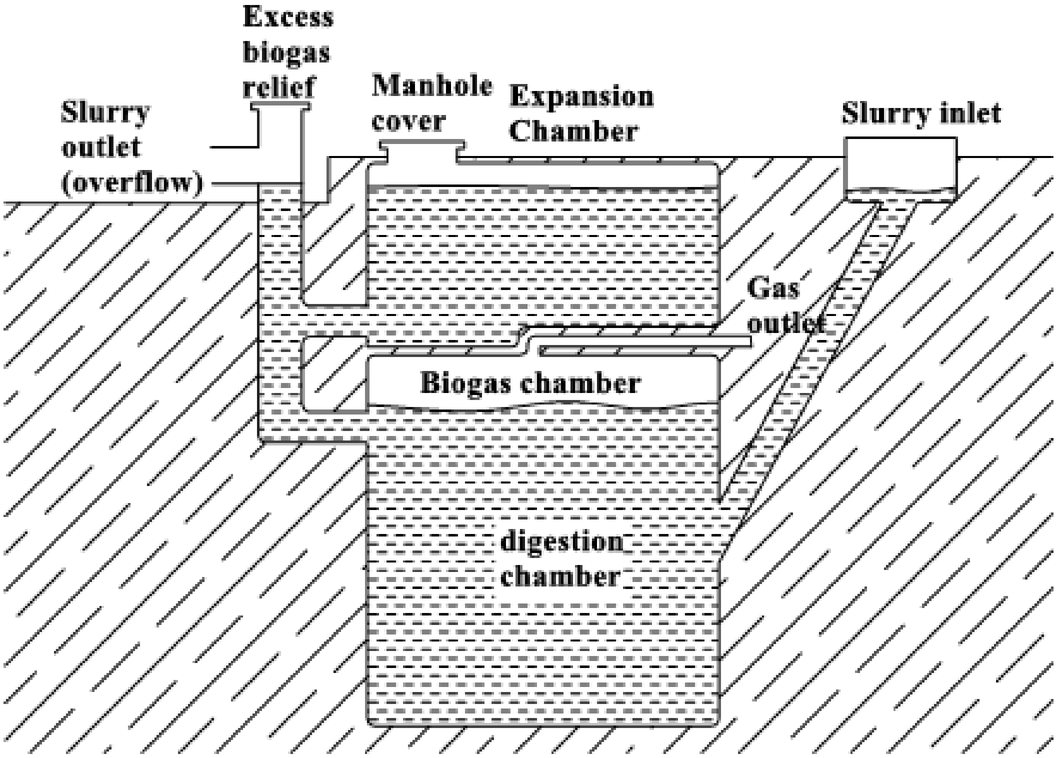

Figure 2.8: The Little green monster digester (Department of Energy et al., 2014)

It has an inlet pipe and expansion chamber into which displaced slurry moves. The tank has an expected life of 20 years (Department of Energy et al., 2014). It is placed underground. When gas has been produced it accumulates in the arch of the digestion chamber, displacing slurry into the expansion chamber. When the expansion chamber fills up, extra slurry displaced overflows out of the system through the slurry outlet nozzle. In the event of excessive gas stored before withdrawal for use, the safety measure is that the slurry is displaced and at a certain point, gas begins to exit the digestion chamber together with displaced slurry to be vented into the atmosphere. This is a breather mechanism. The breathing chamber volume is the effective volume of slurry that can be displaced before the gas starts escaping through the piping into the atmosphere. When extracting the gas, the difference in liquid levels of the top and bottom chambers supply the back pressure in order to make the gas flow out of the gas connection. The gas connection comes out of the top of the bottom chamber, through the top chamber and out to the point of use. Gas can be extracted to the point when the top chamber is completely empty and no back pressure exists any more. This digester however has a limitation when it comes to the need for the clean-up and removal of solid sludge deposited on the floor of the digester. It is recommended by the manufacturer that when doing clean-up the digester must never be completely emptied since its walls would yield to the pressure of the surrounding earth and reduce the digester volume permanently or collapse the digester inwardly (Department of Energy et al., 2014). This raises challenges to the maintenance of this kind of a digester. The design also does not have provision for efficient agitation of the slurry which hinders efficient gas production. The biogas production during winter will inevitably be slower than in summer because of the colder soil temperatures. Finally, the need for excavation is another limitation of the digester design.

#### ***Agama Fixed dome***

The Agama fixed dome digester was developed in South Africa and its customers include farmers, rural schools, eco-lodges, and “green” households which are mainly rural (Cheng et al., 2014). This digester is a plastic roto-mould digester which uses the operating principle of the traditional fixed dome digester. It is however a greatly modernized version which has the advantages of being leak proof and anticorrosive since it is made out of plastic, above ground hence requiring no much excavation save for that meant for the effluent sump and thus feasibly suitable in many settings (Cheng et al., 2014). This design has an advantage that it efficiently handles human waste which is rich in nitrogen content thus working well by increasing adjusting the carbon – nitrogen (C/N) ratio (Ghosh & Bhattacherjee, 2013).  However, the absence of an agitation device is a limitation in this design as solids tend to deposit at the base. There is therefore the need for constant maintenance to clean the digester. The design also supplies gas at variable pressure which is a limitation. Figure 2.9 shows an Agama fixed dome digester.

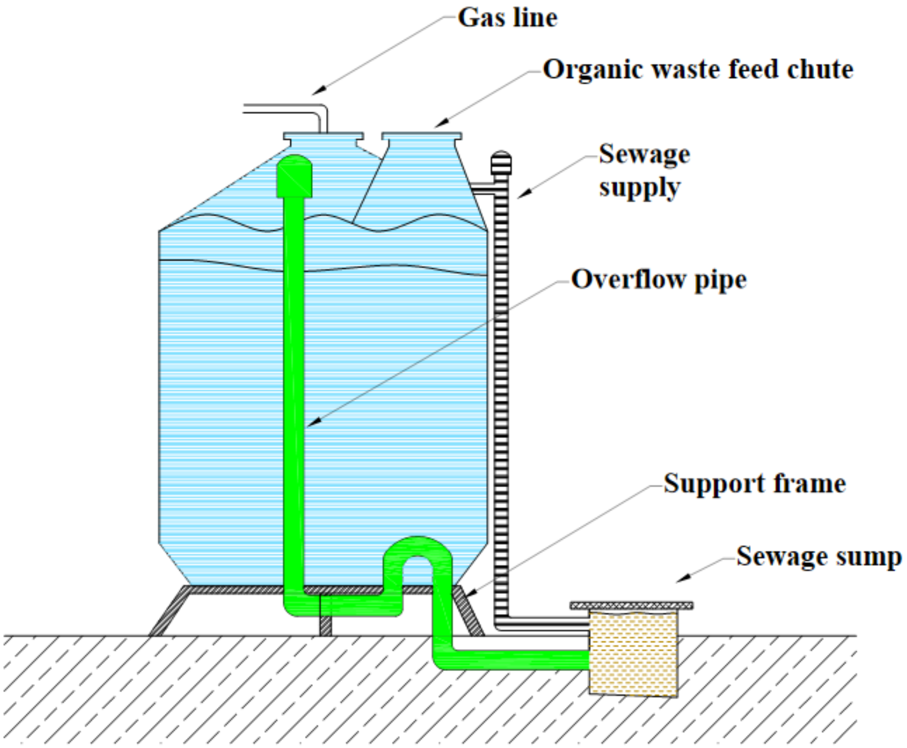

Figure 2.9: Agama fixed dome digester (Cheng et al., 2014)

#### 2.8.1.9 In-situ cast concrete digester (Puxin)

The in-situ cast concrete (Puxin) digester finds its application on a household scale to treat sewage and food wastes. It is a hydraulic biogas digester that designed to solve the technical problems thus enhancing, the advantages of the traditional fixed and floating dome type digester designs. Its construction is done using a shutter system that consists of small bolted steel panels which is erected in the form of an igloo around which concrete is cast to form the digester. The shutter can then be dismantled once the concrete has gained sufficient strength and used again for another digester. The digester basically consists of a belly, neck, plastic fiber gas holder, an inlet pit and an outlet pit. The digester basically functions as a hydraulic system where the entire digester is flooded with water at the same level in the inlet, digester neck and outlet (Shenzhen Puxin Science and Technology Company Limited, n.d.).

Since the decomposition of the material takes place under water, ideal anaerobic conditions that are crucial for the production of methane are provided within the digester. The water also creates a constant pressure under which the biogas formed will flow. Figure 2.10 shows an In situ cast concrete digester (Puxin).

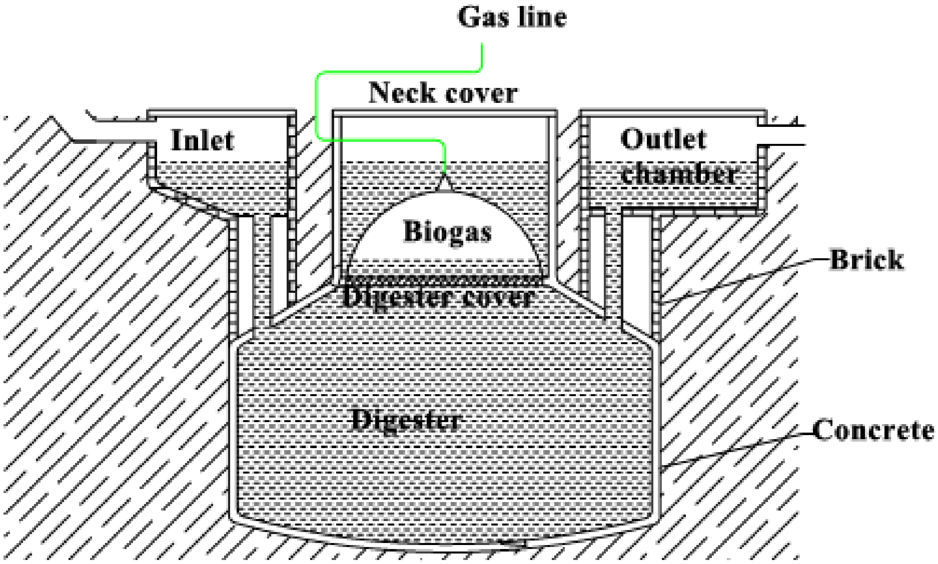

Figure 2.10: The In-situ cast concrete digester ( SPST Co. Ltd., n.d.)

As biogas is produced in the bottom of the digester belly, it rises upwards and collects in the dome. As the volume of gas increases, it displaces the water downwards resulting in an upward pressure on the gas due to the equal and opposite reaction of the displaced water. This ensures that the collected biogas in the dome is always under constant pressure which can get up to 8 kPa which is a major advantage for the efficient running of most gas appliances (SPST Co. Ltd, n.d.).

The digester is so easy to clean hence any type of organic material can be used as feeder material unlike in the brick and mortar fixed dome digester where it is not practical to empty the digester (Singh et al., 1997). Organic waste such as leaves, straw and grass do not decompose to the same extent as manure and will always leave solid waste after decomposition. This spent material needs to be removed from the digester before the digester can be reloaded with new material. The light weight Puxin digester dome can easily be opened and the solid waste removed, making the system suitable for use of organic waste as feeder material. This is a major advantage for applications where animal manure is not available in the necessary quantities but enough organic material is available. BiogasSA is the South African agent for the patented in-situ cast concrete digester from Puxin. The design of the Puxin digester not only ensures long term structural and functional integrity due to the high strength under compressive forces, of the concrete, but also ensures biogas production at a constant pressure. The Puxin digester design however, has the limitation that it is only suitable for installation in areas where the ground is good enough for economic excavation.

### 2.8.1.10 Fibre reinforced plastic (FRP) digester

There are 2 types of FRP digesters:

1. A top-half FRP digester consisting of a top half made of FRP and a bottom half made of concrete.
2. A complete FRP.

Figure 2.11 shows the 2 types.

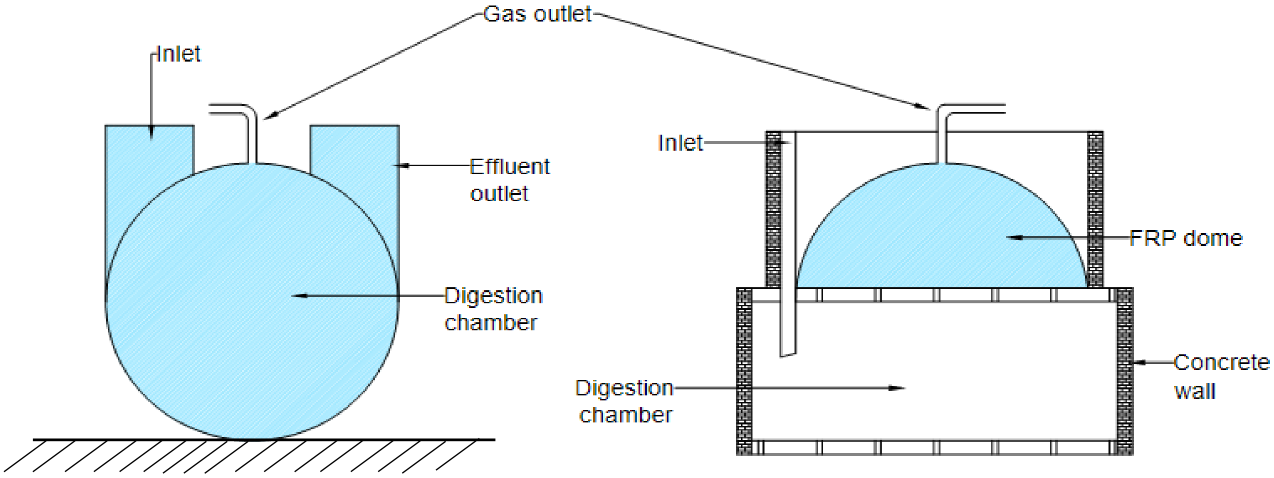

Figure 2.11: Complete FRP digester (left) and Top-half FRP digester (right) (Cheng et al., 2014).

The installation of a complete FRP digester is much easier than that of a top-half FRP digester though the top-half FRP digester has two advantages over complete FRP digester in that its less expensive and cannot sink in case of a weak ground (Cheng et al., 2013). A possible disadvantage of PFRs is that concentrations of substrate are highest where the influent enters the reactor which may result in the production of excess organic acid which drop the pH thus causing digester instability (Rowse, 2011).

#### 2.8.1.11 Plastic soft (PS) Digester

A PS digester is characterized by a soft material and convenient packing. It may be laid in a concrete structure, a chamber or directly in a pit. The most popular materials for PS digesters are poly-vinyl chloride (PVC), poly ethylene (PE), and red mud plastic (RMP).

#### 2.8.1.12 Plastic hard (PH) digester

PH digesters are made of hard materials such as hard PVC, ABS (Engineering Plastics), high density polyethylene (HDPE) and other modified plastics. This kind of digester is composed of several pieces of mechanically pressed sheets and can be easily assembled onsite. The technology is characterized by high production efficiency and low labor intensity. It has the following properties: high strength, anti-aging, corrosion resistant, no leakage, good tightness, lightweight and convenient transportation, fast and easy construction and installation and long service life of more than 30 years (Cheng et al., 2014). It can be installed in any kind of soil and under any environmental condition.

### 2.8.2 Medium scale digesters

Medium scale (commercial) digesters are biogas systems of a capacity between 25-250 kW (Biogas-info, 2013). Their use is found in the generation of electricity and the target market is conference/community centers, small commercial facilities such as abattoirs, dairy factories and farms. Typical designs under this category are the lagoon digester, plug flow digester, complete mix digesters (CSTR) and up-flow sludge blanket digester (UASB) (SABIA, 2016).

### 2.8.3 Large scale digesters

Large scale digesters (>250 kW) are large facilities (agricultural/industrial) digesters such as municipal solid waste, abattoirs, farms and wastewater treatment facilities for example; Mariahill (Durban 1MW, 2003-2010) and Bisasar (Durban 6.5 MW, 2010). In the agricultural or industrial digester category are the lagoon, plug flow, complete mix (CSTR) and up-flow sludge blanket (UASB) digesters. This category comprises the small and medium-scale commercial digesters, a scale which is defined as biogas systems having between 25-250 kW electrical capacity (Biogas-info, 2013).

The applications of the gas from these digesters are direct gas use for heating, lighting and generation of electricity and the target market comprises community centers, small commercial facilities such as abattoirs, dairy factories and farms. In South Africa there are agricultural scale digester installations at CAE, Humphries Boerdery outside Bela-Bela which has an electrical capacity of 30 kW, Jan Kemdorp Abattoir iBERT with 100 kW, Cullinan with 190 kW, Robertson with 150 kW and Jacobsdal with 150 kW electrical capacities (Town, 2015).

#### 2.8.3.1 Plug flow digester

The first documented use of this type of digester design was in South Africa in 1957 (Ghosh & Bhattacherjee, 2013). The plug flow digester is a low rate system where the substrate flows as a plug and there is no longitudinal mixing of the substrate from inlet to outlet (Lusk, 1998).
The substrate flowing into the digester displaces digester volume and an equal amount of material flows out. This substrate is thick enough to keep particles from settling to the bottom and very little mixing occurs resulting in the substrate moving through the digester as a plug. This digester design has a constant volume, but produces biogas at a variable pressure. It consists of a narrow and long tank with an average length to width ratio of 5:1 (Rajendran et al., 2012). The inlet and outlet of the digester are located at opposite ends above the ground, while the remaining part of the digester is buried in the ground at an angle to the horizontal. As fresh substrate is added from the inlet, the digestate flows towards the outlet at the other end of the tank. The inclined position makes it possible to separate acidogenesis and methanogenesis longitudinally, thus producing a two-phase system. In order to avoid temperature fluctuations during the night and maintain the process temperature, a gable or shed roof can be used to cover the digester and insulate it both during day and night. The advantages of this digester design include easy installation, easy handling, adaptation to extreme conditions at high altitudes with low temperatures, very low capital cost, simple design and a reasonable retention time.

Disadvantages include the absence of agitation, slow solid conversion, low biogas production and the need for periodic cleaning (Ghosh & Bhattacherjee, 2013). Plug flow designs are suitable for manure and operating semi-continuously with a HRT between 20 and 30 days and a solid contents varying between 11 and 14%. These digesters do not have moving parts, reducing the risks for failure (Rajendran et al., 2012).

#### 2.8.3.2 Lagoon digester

This digester design is a passive system which has the advantage of low maintenance requirements. It captures biogas under an impermeable cover. A lagoon is a waste storage as well as a waste treatment system with two cells (Lusk, 1998). The first cell of the lagoon is covered and the second cell is uncovered and both cells are needed for the system to operate efficiently. The liquid level on the second cell must rise and fall to create storage while the level on the first cell remains constant to facilitate the decomposition of waste. Since they are not heated, the temperature of covered lagoons follows seasonal patterns. Methane production drops when lagoon temperatures dip below 20$^{o}$C (Hamilton, 2014). Sludge can be stored in lagoons for up to 20 years which means that the methane-forming microorganisms will also remain in the covered lagoon for up to 20 years (Hamilton, 2014). This also implies the trapping of much of the fertilizer nutrients, particularly phosphorus in the covered lagoon for a long time. The retention time is generally 30 to 60 days depending on the size and age of the lagoon (Samer, 2012). An example of a lagoon installation in South Africa is the 120 kW installation north of Pretoria (Town, 2015). They are not heated and considered ambient temperature digesters. Retention time is usually 30–45 days or longer depending on lagoon size (Penn State University, 2014). The gas produced is trapped under the impermeable cover as anaerobic decomposition of the waste progresses. A lagoon digester work best for liquid manures with less than 2% total solids and is very cheap and highly effective in reducing odors even in cold climates (Pillars, n.d.). Operating within the psychrophilic temperature range, there is no need for heating and the design is also good for seasonal harvesting while it requires very low capital to excellently handle liquid waste. The design however has the disadvantages: high retention times (30-60 days) due to slow solids conversion, bacteria and liquid have limited contact since there is no agitation, biogas production is low, periodic cleaning is necessary and maintenance of the lagoon is difficult (Ghosh & Bhattacherjee, 2013).

#### 2.8.3.3 Complete mix digester

A complete mix digester is basically a tank in which substrate is heated and mixed with an active mass of anaerobic microorganisms (Ghosh & Bhattacherjee, 2013). An example is the up-flow anaerobic sludge blanket (UASB) digester. The incoming feed displaces the digester volume and an equal amount of liquid flows out. The methane forming microorganisms flow out of the digester with the displaced digestate. Biogas production is maintained by adjusting the volume such that liquids remain in the digester for 20 to 30 days (Deepanraj et al., 2015). Retention times can be shorter for thermophilic systems. The digester can be continuously or intermittently mixed. Sometimes the process takes place in more than one tank. For instance, acidogenic bacteria can break down manure in one tank and then methanogenic bacteria convert the formed organic acids to methane in a second tank. Complete mix digesters work best when the substrate contains 3 - 10 % total solids (Lusk, 1998). Digester size can be an issue at lower solids concentrations. Lower solids mean greater volume which implies the need for a larger digester to retain the microbes in the digester for 20 to 30 days (Doug, 2012). The advantages of a complete mix digester are: high biogas production, the ability to handle a wide range of concentrations, efficient agitation within the reactor, short retention time and effective contact of bacteria and substrate and the disadvantages are: high capital and energy costs, loss of anaerobic microorganisms from the digester and the need for maintenance of the mechanical parts of the digester periodically (Hamilton, 2014). The feed should contain 3 to 10% total solids (Ghosh & Bhattacherjee, 2013). Typical application of complete mix digesters in South Africa is in abattoirs, food processing plants and fruit/vegetable packaging (Town, 2015).

#### 2.8.3.4 Fixed film digester

The fixed-film digester consists of a tank filled with plastic media. A fixed film digester vessel is filled with an inert medium or packing that provides a very large surface area for microbial growth (Pennyslavia State University, 2003). The media supports a thin layer of anaerobic bacteria termed bio-film from where the digester name "fixed-film" is derived (Ghosh & Bhattacherjee, 2013). As the waste manure passes through the media, biogas is produced. Like covered lagoon digesters, fixed-film digesters are best suited for dilute waste streams typically associated with flush manure handling or pit recharge manure collection. Fixed-film digesters can be used for both dairy and swine wastes. The immobilization of the bacteria as a bio-film prevents washout of slower growing cells and provides biomass retention independent of hydraulic retention time (HRT). The Fixed film digester is best suited to process manure with 1 - 3 % total solids and retention time is usually 3 to 5 days (Ghosh & Bhattacherjee, 2013). Some of the advantages of the fixed film digester design are: short retention time, easy construction, easy operation, moderate biogas yield and the ability to retain anaerobic microorganisms within the digester irrespective of the short retention time. The disadvantages are: the need for periodic cleaning and replacement of the film, plugging is usually a problem when high solids develop within the digester and the absence of uniform temperature distribution (Darwin et al., 2014).

### 2.8.4 Large scale commercial digesters

Large scale digesters are the digesters with an electrical capacity >250 kW and these are large facilities such as municipal solid waste, abattoirs, farms and wastewater treatment facilities. Installations of large scale digesters in South Africa are Mariannhill (Durban, 1MW)- (2003-2010), Bisasar road (Durban, 6.5 MW)-2010, Chloorkop landfill gas project (EnviroServ, 2010), Ekhurleni landfill gas project (2010), Robinson deep in city of Johannesburg (19 MW, 2011), Biogas digesters at SA breweries (SAB), Alrode up-flow anaerobic sludge blanket/UASB -2005, Newlands UASB -2007, Rosslyn, Prospection and Ibhayi. The anaerobic digesters for industrial & municipal wastewater in South Africa are Cape flats biogas digester-dewatering sludge (2003), Ceres fruit farm-UASB digester, Veolia (1998), PetroSA (Biotherm), 4.2 MW (2008), 2013 and the Northern wastewater treatment works, biogas to electricity project (1.1 MW) (Department of environmental affairs, 2016). The upcoming large scale biogas digesters are Gauteng & Western Cape-Bio2Watt (3 & 2 MW) and Gauteng-Lesedi 4.2 MW (Benefits et al., 2014). Other countries implementing national biogas programs, such as Nepal, Bangladesh, Vietnam, and Myanmar, are also testing PBDs (Cheng et al., 2014). The initial models are mostly imported from China, as factory production of PBDs is nonexistent in other developing countries, and the quality of locally produced PBDs is relatively low. As mentioned in previous sections, international cooperation could bring new markets to the Chinese PBD industry (Cheng et al., 2013) – a justification for the current design by the author of the present work.

## 2.9 USE OF A GREENHOUSE FOR DIGESTER TEMPERATURE CONTROL

The use of a greenhouse for biogas digester temperature control is an attractive way to solve the problem of poor gas production and quality due to low and fluctuating operation temperatures during the anaerobic digestion process. A greenhouse structure causes an accumulation of heat within it when exposed to the short wave, high frequency radiation from the sun (Conradie, Researcher, Published, Building, & Essential, 2010). This energy can be used to raise the slurry temperature to the desired optimum for efficient anaerobic digestion.

### 2.9.1 Heat transfer processes in a greenhouse

The temperature conditions inside a greenhouse enclosure with a radiation absorbing body inside is a dynamic system of energy transfer. The energy transfer system is influenced by the environmental conditions such as the global solar radiation, air temperature, sky temperature, wind speed and humidity outside the greenhouse. The structure and orientation of the greenhouse and its control actuators such as ventilation also influence energy transfer processes within the greenhouse (Lau & Staley, 1989). The greenhouse effect in a greenhouse structure takes place when shortwave radiation consisting mainly of ultraviolet (UV) radiation from the sun is transmitted through the greenhouse cover. The amount of radiation entering the greenhouse depends on the transmittance of the cover used. This implies that only a fraction of the incident radiation is transmitted through the cover into the greenhouse. The other fraction is either absorbed by the cover or reflected back into the atmosphere. Inside the greenhouse, the transmitted radiation energy is absorbed by objects within the greenhouse or some parts of the greenhouse structure such as the floor. These absorbing surfaces heat up as a result and re-radiate longwave infrared (IR) thermal energy into the greenhouse space (Conradie, 2010). The thermal radiation has less energy and cannot be transmitted through the greenhouse cover back into the atmosphere. This results in a build-up of heat energy within the enclosed greenhouse space (Kalogirou, 2014). Figure 2.12 shows the heat transfer processes in a greenhouse.

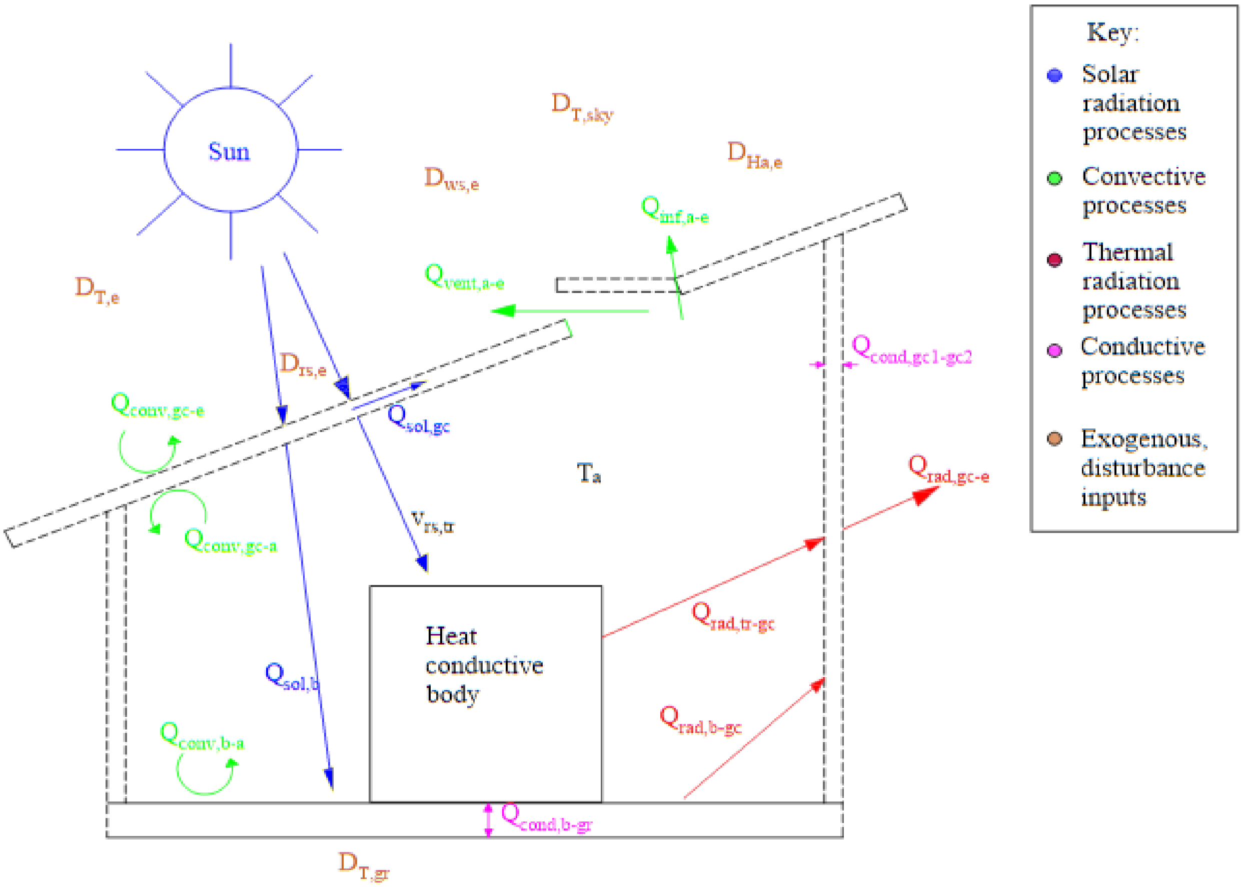

Figure 2.12: Heat transfer processes in a greenhouse

Net heat gain within the greenhouse depends on the balance between the amount of solar radiation received and the amount of thermal radiation lost (Sustainable energy authority Victoria, 2002). Thermal radiation loss from the greenhouse occurs through conduction through the covering, ventilation and infiltration (Kalogirou, 2014). The temperature of the air inside the greenhouse structure at any given time can be predicted by equation [2.3]:

$$C_{p,a}\rho_a V\left(\frac{c_{vol,g}}{c_{area,b}}\right)\frac{dT_a}{dt} = Q_{sol,a} + Q_{conv,b-a} + Q_{cond-conv,a-e} - Q_{ven,a-e} - Q_{\inf,a-e} \tag*{[2.3]}$$

where: $\frac{dT_a}{dt}$ - Rate of change of the greenhouse air temperature

$C_{p,a}$ -specific heat capacity of air inside the greenhouse

$\rho_a$ -density of the air inside the greenhouse

$\frac{c_{vol,g}}{c_{area,b}}$ - effective height of the greenhouse (greenhouse volume/base surface area)

$Q_{sol,a}$ - solar radiation absorbed by the air

$Q_{conv,b-a}$ - Heat transfer by convection of air with the greenhouse base

$Q_{cond-conv,a-e}$ - Heat transfer by convection and conduction in the greenhouse cover between the inside and outside air

$Q_{vent,a-e}$ - Heat lost by natural ventilation from inside air to outside air

$Q_{\inf,a-e}$ - Heat lost by infiltration losses

The solar radiation absorbed by the air is given by equation [2.4]:

$$Q_{sol,a} = c_{asw,a}v_{rs,tr} = c_{asw,a}v_{trsw,gc}D_{rs,e} \qquad [2.4]$$

where;

$c_{asw,a}$ - shortwave absorption coefficient of the air inside the greenhouse

$v_{rs,tr}$ - solar radiation transmitted through the cover into the greenhouse and its given by the equation: $v_{rs,tr} = v_{trsw,gc}D_{rs,e}$ [2.5]

$v_{trsw,gc}$- short wave heat transmission coefficient of the greenhouse cover

$D_{rs,e}$ - global solar radiation

The convective flux of air inside the greenhouse with the greenhouse base is a function of the temperature difference between the greenhouse base and the air. It is given by the equation:

$$Q_{conv,b-a} = c_{conv,b-a}\left(T_b - T_a\right) \quad [2.6]$$

where:

$c_{conv,b-a}$ - convection coefficient

$T_b$ - temperature of greenhouse base

$T_a$ - temperature of air inside the greenhouse

The heat transfer process by convection and conduction in the cover between the outside and inside air is directly proportional to the temperature difference between the outside air and the inside air. Equation [2.7] gives the heat transfer by convection and conduction:

$$Q_{cond-conv,a-e} = c_{cond-conv,a-e}\left(T_a - D_{T,e}\right) \quad [2.7]$$

where: $c_{cond-conv,a-e}$ is a conductive and convective thermal loss coefficient

$D_{T,e}$ - temperature of air outside the greenhouse

The ventilation and infiltration processes occur simultaneously since infiltration is included as a constant effect in the ventilation flux. Greenhouse ventilation is an air-exchange process that replaces the warm air inside the greenhouse with cooler outside air in order to reduce the temperature within the greenhouse (Buschermohle & Grandle, 2012; Karlsson, 2014). Air expands when heated, thus increasing the pressure in the greenhouse constant volume and to release this pressure the air has to be vented out through openings in the structure and replaced with cooler, denser and low volume air drawn from the greenhouse surroundings (Bartok, 2000). Heat transfer to the outside air due to ventilation and infiltration is given by equation [2.8]:

$$Q_{vent,a-e} + Q_{\inf,a-e} = \frac{c_{\rho,a} c_{p,a}}{c_{area,b}} V_{vent,flux}\left(T_a - D_{T,e}\right) \quad [2.8]$$

where: $V_{vent,flux}$ is the ventilation flux, given by:

$$V_{vent,flux} = c_{vent,n} c_{vent,l} c_{vent,w} D_{ws,e}\left(\alpha_v U_{vent}^{\beta v}\right) + V_{loss} \quad [2.9]$$

$c_{vent,n}$ - number of vents

$c_{vent,l}$ - length of the vents

$c_{vent,w}$ - width of the vents

$\alpha_v$ and $\beta_v$ - are tuning parameters which can show small variations between the leeward and windward ventilation sides according to actual measurements

$U_{vent}$ - percentage or normalised aperture of the vents

$V_{loss}$ - the leakage when vent is closed

$D_{ws,e}$ - wind speed outside the greenhouse

The amount and intensity of solar radiation transmitted into the greenhouse through the cover depends on the transmissivity of the cover to shortwave high frequency radiation, solar radiation which is a function of time of the day and year, the local latitude and the greenhouse surface orientation (Colorado State University, 1978).

#### 2.9.1.1 Transmissivity of greenhouse cover to short wave radiation

The transmissivity of a cover to short wave radiation should be considered together with other factors such as durability, cost of construction and maintenance, type of framing that can support the cover and availability. Table 2.3 shows the transmittance values of several common greenhouse cover materials.

Table 2.3: Greenhouse covering solar transmittance values (Bellows, 2008).

| **Cover** | **Transmittance (%)** |
|---|---|
| Glass-single | 85-95 |
| Glass-factory sealed double | 70-75 |
| Polyethylene-single | 80-90 |
| Polyethylene-double | 60-80 |
| Impact modified acrylic-double | 85 |
| Fiber reinforced plastic | 85-90 |
| Polycarbonate-double wall rigid | 83 |

#### 2.9.1.2 Solar radiation

Solar radiation is the sun’s radiant energy incident per unit area of a surface and is expressed in kWh/m$^2$ (Conradie et al., 2010). It is also referred to as solar insolation or peak sun hours. The total global solar radiation comprises the direct, diffuse and reflected radiation components. Direct radiation is incident on a surface normal to the sun’s rays while diffuse radiation is scattered and reflected radiation incident on the surface (Colorado State University, 1978). The typical solar irradiance on a terrestrial surface facing the sun on a clear day around the solar noon at sea level is 1000W/m$^2$ (Conradie et al., 2010). This is the irradiance used as a rating condition used for PV modules and arrays (Jim dunlop solar, 2012). A pyranometer is used to measure the total solar irradiance (solar power) (Kharseh, n.d.).

The orientation of a PV array, greenhouse or any other solar collector can be defined in terms of the collector tilt angle which is the angle at which the collector surface lies from the horizontal plane or the solar incidence angle between the sun’s rays and the normal to the collector surface. Maximum energy would be intercepted by a collector if the plane surface were to track the sun across the sky so that the rays would always be perpendicular to the plane (Conradie et al., 2010). This would mean both following the sun as it moved from east to west during the day and changing the collector tilt from day to day. Tracking is however not feasible for greenhouse applications (Colorado State University, 1978).

Since tracking is impractical, tilting the collector so that it is approximately perpendicular to the sun's rays at solar noon during the months when maximum heat collection is desired, is an attractive compromise (Colorado State University, 1978). This is achieved by tilting the collector surface from the horizontal plane at an angle equal to the local latitude of a given location (Jim dunlop solar, 2012). In the northern hemisphere the collector should be tilted to the south and in the southern hemisphere it should be tilted to the North (Colorado State University, 1978; Jim dunlop solar, 2012).

The amount of solar radiation incident on a tilted collector surface is the component of the incident solar radiation which is perpendicular to the module surface. The following equation shows how to calculate the radiation incident on a tilted surface, $S_x$ given the solar radiation measured on a horizontal surface, $S_h$.

$$S_x = \frac{S_h Sin(\alpha + \beta)}{Sin\alpha} \qquad [2.10]$$

where:

$\alpha$ - elevation angle

$\beta$ - tilt angle of the module measured from the horizontal.

Using the above relationship, the solar radiation incident on a greenhouse cover surface can be calculated. The greenhouse can also be designed in such a way as to maximize solar radiation transmission by tilting the collector surface at an angle equal to the latitude of the greenhouse location. Tilting the greenhouse in the north-facing or south-facing directions can also increase the surface area for short wave radiation incidence and hence increase the amount of transmitted

### 2.9.2 Greenhouse thermal mass

With a biogas digester inside, a greenhouse can behave as a thermal mass. This is due to the high density and thermal capacity and low conductivity of the substrate slurry which make it a good thermal mass (Hampton, 2010; Radmanović, Đukić, & Pervan, 2014). Heat can slowly be absorbed and stored in the mass during the heating hours of the day and slowly emitted when the surroundings become cooler, without reaching thermal equilibrium (Brandemuehl et al., 1990). This reduces temperature fluctuations and its effects within the greenhouse and the slurry thereby increasing biogas production.

#### 2.9.2.1 Site selection for greenhouse

Since a greenhouse is affected by outdoor elements such as the direction and intensity of wind, sun, snow, and frost it has to be placed where it is safe from these adverse weather conditions for optimal performance (Defacio, Pickerel, & Rhyne, 2010). This can be enhanced by making the greenhouse a portable unit.

## 2.10 MILD STEEL LOW PRESSURE VESSEL DESIGN PARAMETERS

A metallic digester placed within a greenhouse to absorb solar and thermal radiation for efficient biogas production functions as a pressure vessel. A pressure vessel is any closed vessel with a diameter, $\phi > 150\,mm$ and being subjected to a pressure difference, $\Delta P > 0.5\,bars$ (Coulson and Richardson, 2003). In designing a pressure vessel, the vessel function and suitable material of construction in relation to corrosion resistance, heating requirements, thermal conductivity, ease of fabrication and welding, any internal fittings required, operating temperature and pressure, vessel dimensions, type of vessel heads to be used, and the cost of construction have to be considered.

### 2.10.1 Vessel function

A biogas digester meant to produce and contain the produced biogas before use should be designed as a pressure vessel. The digester has to be designed in such a way that it can operate within the mesophilic temperature range as recommended in the previous sections and at a pressure above atmospheric to avoid a negative pressure drop which would suck atmospheric air into the digester causing an explosion (GTZ, 2007).

### 2.10.2 Design pressure

A vessel must be designed to withstand the maximum possible pressure to be exerted by the gas produced inside it when in operation.

### 2.10.3 Design temperature

Different materials of construction have different design stress allowances and for metals, the maximum allowable design stress decreases with increasing temperature and hence the temperature at which the design stress is evaluated should be taken as the maximum working temperature of the material (Coulson and Richardson, 2003).

### 2.10.4 Minimum practical wall thickness

Under internal pressure a vessel will expand slightly. It may fail along the longitudinal section (circumferentially) or it may fail across the transverse section (longitudinally). Thus the wall of a cylindrical shell subjected to an internal pressure has to withstand circumferential and longitudinal tensile stresses (Coulson and Richardson, 2003). This is achieved by designing a minimum wall thickness that can ensure that the pressure vessel is sufficiently rigid to withstand the stresses subjected on it, its own weight and any incidental loads. An allowance for corrosion in the case of use of a material that can be affected by corrosion over time should be factored in as well. The corrosion allowance is the additional thickness added to allow for material loss by corrosion and erosion, or scaling. A corrosion allowance of 2 mm is usually added (Khurmi and Gupta, 2005).

#### 2.10.4.1 Thickness of the cylindrical section of a low-pressure vessel

Assuming that:

1. The effect of curvature of the cylinder wall is neglected
2. Stresses are only in two dimensions since the cylinder wall is very thin relative to the other dimensions of the cylinder.
3. The tensile stresses are uniformly distributed over the section of the walls
4. The effect of the restraining action of the heads at the end of the pressure vessel is neglected;

The circumferential stress in a cylindrical pressure vessel wall can be calculated using Figure 2.13:

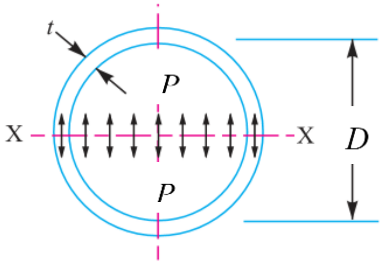

Figure 2.13: Circumferential cross-section of a cylindrical vessel

where:

$P$ - intensity of internal pressure

$D$ - internal diameter of the vessel

$l$ - length of the cylindrical section

$t$ - thickness of the cylindrical wall

$f_1$- circumferential stress for the material of the cylindrical vessel

The total force acting on a longitudinal section (X-X) of the vessel is given by:

$$F = PDl \tag{2.11}$$

The total resisting force acting on the cylinder is given by:

$$F_r = 2tf_1 \tag{2.12}$$

Equating [2.11] with [2.12] gives;

$$f_1 = \frac{PD}{2t} \tag{2.13}$$

Figure 2.14 shows the longitudinal cross-section of a cylindrical vessel

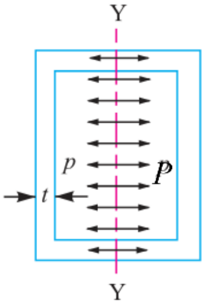

Figure 2.14: Longitudinal cross-section of a cylindrical vessel

The total force acting on the transverse section (Y-Y) is given by:

$$F = \frac{P\pi D^2}{4} \tag{2.14}$$

and total resisting force is given by:

$$F_r = f_2\pi Dt \tag{2.15}$$

where: $f_2$ - Longitudinal stress.

Equating [2.14] with [2.15] gives:

$$f_2 = \frac{PD}{4t} \tag{2.16}$$

The principal stress between the two is therefore $f_1$, and substituting the inner diameter, $D$ with the mean diameter, $D+t$ in equation [2.13] gives the minimum thickness, $t_c$ required to resist internal pressure in a cylindrical pressure vessel:

$$t_c = \frac{P_i D_i}{2f - P_i} \qquad [2.17]$$

where:

$P_i$ - Working pressure (N/mm$^2$)

$D_i$ - Vessel diameter (mm)

$f$ - Design stress

### 2.10.4.2 Thickness of the top and bottom sections of a low-pressure vessel

There are several types of pressure vessel heads that can be used which include the flat plate flange, tori-spherical and hemispherical vessel heads. The design equations used to determine the thickness of the heads are based on the analysis of the compressional and tensile stresses under which the head would have to operate. These analyses are done according to the American Society of Mechanical Engineers (ASME) code, section VIII. For the flat plate flange, the major threat is the deflection of the neutral axis in the central part of the plate hence the optimum thickness, $t_f$ is calculated from equation [2.18] (Coulson and Richardson, 2003; Khurmi and Gupta, 2005):

$$t_f = C_p D_i \sqrt{\frac{P_i}{f}} \qquad [2.18]$$

where: $C_p$ - edge support coefficient

In a tori-spherical head, there are two junctions, that is; between the cylindrical section and the head, and that at the junction of the crown and the knuckle radii. The bending and shear stresses caused by the differential dilation that will occur at these points must be taken into account in the design of the heads. The ratio of the knuckle radius to crown radius should be made not less than

6/100 to avoid buckling. The thickness, $t_t$ for the tori-spherical bottom is given by equation [2.19] (Coulson and Richardson, 2003; R.S. Khurmi J.K. Gupta, 2005):

$$t_t = \frac{P_i R_c C_s}{2fJ + (C_s - 0.2)} \qquad [2.19]$$

where:

$R_c$ - crown radius,

$P_i$ - Internal pressure

$J$ - Joint factor

$C_s$ - stress concentration factor

The stress concentration factor, $C_s$ for tori-spherical heads is given by:

$$C_s = \frac{1}{4}\left(3 + \sqrt{\frac{R_c}{R_k}}\right) \qquad [2.20]$$

where: $R_k$ - knuckle radius (6% of $R_c$ ).

### 2.10.4.3 Materials of construction

Low carbon steel (mild steel) is the most commonly used engineering material. It is cheap and readily available in a wide range of standard shapes and sizes and can be easily worked and welded. It has good tensile strength and ductility. Carbon steel and iron are not resistant to corrosion, except in certain specific environments, such as concentrated sulphuric acid and the caustic alkalis but they are suitable for use with most organic solvents, except chlorinated solvents though traces of corrosion products may cause discoloration. Mild steel is susceptible to stress-corrosion cracking in certain environments. The corrosion resistance of the low alloy steels (less than 5 per cent of alloying elements), where the alloying elements are added to improve the mechanical strength and not for corrosion resistance, is not significantly different from that of the plain carbon steels.

A wide range of paints and other organic coatings is used for the protection of mild steel structures. Paints are used mainly for protection from atmospheric corrosion. Special chemically resistant paints have been developed for use on chemical process equipment. Chlorinated rubber paints and epoxy-based paints are used. In the application of paints and other coatings, good surface preparation is essential to ensure good adhesion of the paint film or coating.

The life of equipment subjected to corrosive environments can be increased by proper attention to design details. Equipment should be designed to drain freely and completely. The internal surfaces should be smooth and free from crevasses where corrosion products and other solids can accumulate. Butt joints should be used in preference to lap joints. The use of dissimilar metals in contact should be avoided, or care taken to ensure that they are effectively insulated to avoid galvanic corrosion. Fluid velocities and turbulence should be high enough to avoid the deposition of solids, but not so high as to cause erosion-corrosion.

## 2.11 SUMMARY

Biogas is produced in the process of anaerobic digestion. The anaerobic digestion process is a complex biochemical process which involves four simultaneously occurring stages namely; hydrolysis, acidogenesis, acetogenesis and methanogenesis. The factors affecting biogas production include temperature, pH, and slurry agitation, the substrate chemical oxygen demand, ammonium nitrate, total alkalinity, total solids and volatile solids. Of these factors, temperature, pH, and agitation are major factors needing more attention in small scale digesters. Small scale digester designs in current use include the In-situ cast concrete, Brick and motor fixed dome, Bio-bag, Plastic roto-mould and Floating dome digesters. Most of these small scale digesters have poor temperature control and inefficient agitation and hence can only produce small biogas quantities and methane yields. The use of a greenhouse for small digester operation temperature control is an attractive solution to the common limitation of poor temperature control and inefficient agitation. In a greenhouse structure housing a digester, solar radiation is transmitted through the greenhouse cover and a fraction of the transmitted radiation is absorbed by the digester and conducted into the substrate slurry as thermal energy hence raising the slurry temperature. The other fraction is radiated back into the greenhouse space as thermal radiation. This thermal radiation has a longer wavelength than the solar radiation and hence cannot be transmitted back into the atmosphere through the greenhouse cover. Thermal energy therefore accumulates within the greenhouse resulting in the heating of the slurry. Some thermal energy is however lost from the greenhouse to the atmosphere through conduction across the cover, convection from the air to the cover and away, ventilation and infiltration through openings in the greenhouse walls. A digester vessel is considered a low-pressure vessel and the internal pressure to be exerted to the vessel is considered in the determination of the vessel dimensions and wall thickness.

# CHAPTER 3: METHODOLOGY

## 3.1 INTRODUCTION

The design and construction of the agitated portable biogas digester under greenhouse-regulated temperature was achieved through the use of computer application software, workshop equipment and tools at the University of Fort Hare. The performance evaluation of the constructed digester was done using the methods described in section 3.3 of this chapter.

## 3.2 DIGESTER DESIGN

AutoCAD, a computer aided design software was used for designing and drafting the digester in two and three dimensions. The software allows users to use lines, polygons, shapes, text and other visual items to create scale-model blueprints of whatever structure being designed.

For circuit design, TinyCAD was used. With this computer aided design software, circuit designs are created from built-in objects such as wires, junctions, etc., and from imported electrical component symbols, such as diodes and transistors..

## 3.3 DIGESTER CONSTRUCTION

The carbon steel digester vessel was fabricated using mechanical sheet metal roller, hydraulic dishing press, guillotine, welding and drilling machines.

### 3.3.1 Roller

A single-pinch (initial-pinch) 3 roll bender roller was used to roll the mild steel sheet metal into the desired cylindrical shape. This machine works by pinching the metal between two rolls and curving it as it comes in contact with a back forming roll. This curves the metal sheet into a cylindrical form which can be welded together to produce a cylinder. On the machine the upper roll stays in a fixed position while the lower roll has adjustable vertical movement to perform the gripping function (pinching). The third roll (forming roll) is diagonally adjustable. The metal plate to be rolled is inserted into the machine twice in order to pre-bend both ends to ensure a perfectly curved shape and to ensure better closure of the seam after completion.

Figure 3.1 shows the sheet metal pressing machine, guillotine and roller that were used.

(a) (b) (c)

Figure 3.1: Sheet metal pressing machine (a), guillotine (b) and roller (c)

To pre-bend the first end, the plate is inserted into the machine and clamped (pinched) between the top and bottom pinch rolls. The rear bending roll, hydraulically moved diagonally toward the top roll, pushes against the metal plate to bend it into the desired radius. The second end is also treated in the same manner before the metal plate is rolled into a complete cylinder as shown in Figure 3.2. The figure shows how a plate is formed into a tube with a single (initial) pinch plate rolling machine.

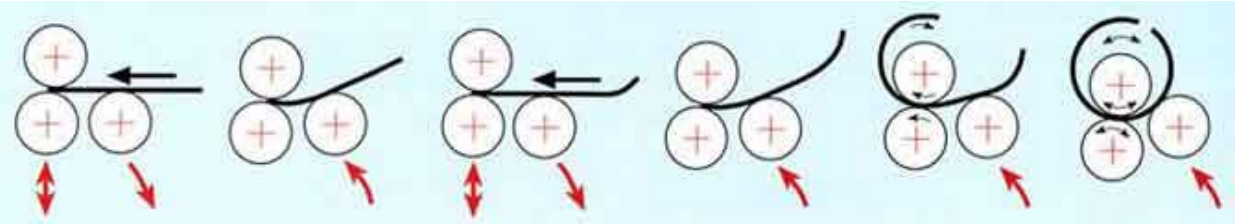

Figure 3.2: Metal sheet rolling steps

The seam is then welded together and a manually moved drop hinge opens one end of the top shaft to allow for the removal of the finished work piece.

### 3.3.2 Guillotine

A mechanically powered guillotine was used to cut the mild steel. The machine consists of a shear table, work-holding device, upper and lower blades, and a gauging device. The shear table is where the workpiece rests on while being cut and work-holding device is used to hold the workpiece in place and keep it from moving or buckling while under stress. The upper and lower blades do the cutting, while the gauging device is used to ensure that the workpiece is cut where it is supposed to be cut. The guillotine clamps the metal with a ram and a moving blade then comes down across a fixed blade to cut the metal.

### 3.3.3 Press

In fabricating the tori-spherical bottom, the metal sheet was first pressed under a hydraulic dishing press (Figure 3.1a) mounted with a die template of the desired crown radius and then curled at the edge using a forming and pressure roller to create the knuckle radius. The template used consists of male and female components that produced the shaped stamping. The male was mounted on the press ram to deliver the stroke action while the female was attached to a bolster plate secured to the press bed. Guide pins were used to ensure alignment between the upper and lower template parts. Figure 3.3 (a) shows the forming and pressure roller.

### 3.3.4 Workshop tools

The construction of the greenhouse and all the fittings was done using workshop tools such as the pliers, thin metal sheet cutter, rivet gun, saw, drilling and welding machines, screw driver, club and claw hammer, measuring tape, painting brushes, etc. To hold the construction material in place while working, a vice grip shown in Figure 3.3 (b) was used.

Figure 3.3: (a) Forming and pressure roller, (b) Vice grip

## 3.4 DIGESTER PERFORMANCE EVALUATION

In this section, a collection of methods and systematic procedures followed in the evaluation and optimization of the performance of the biogas digester designed in previous sections is given. This involves the collection of the substrate that was used, the apparatus, reagents and procedure followed in the determination of substrate physico-chemical properties before, during and after digestion, the measurement of digester operation parameters, determination of biogas chemical composition and the storage of data for analysis. Figure 3.4 shows the performance evaluation flow chat.

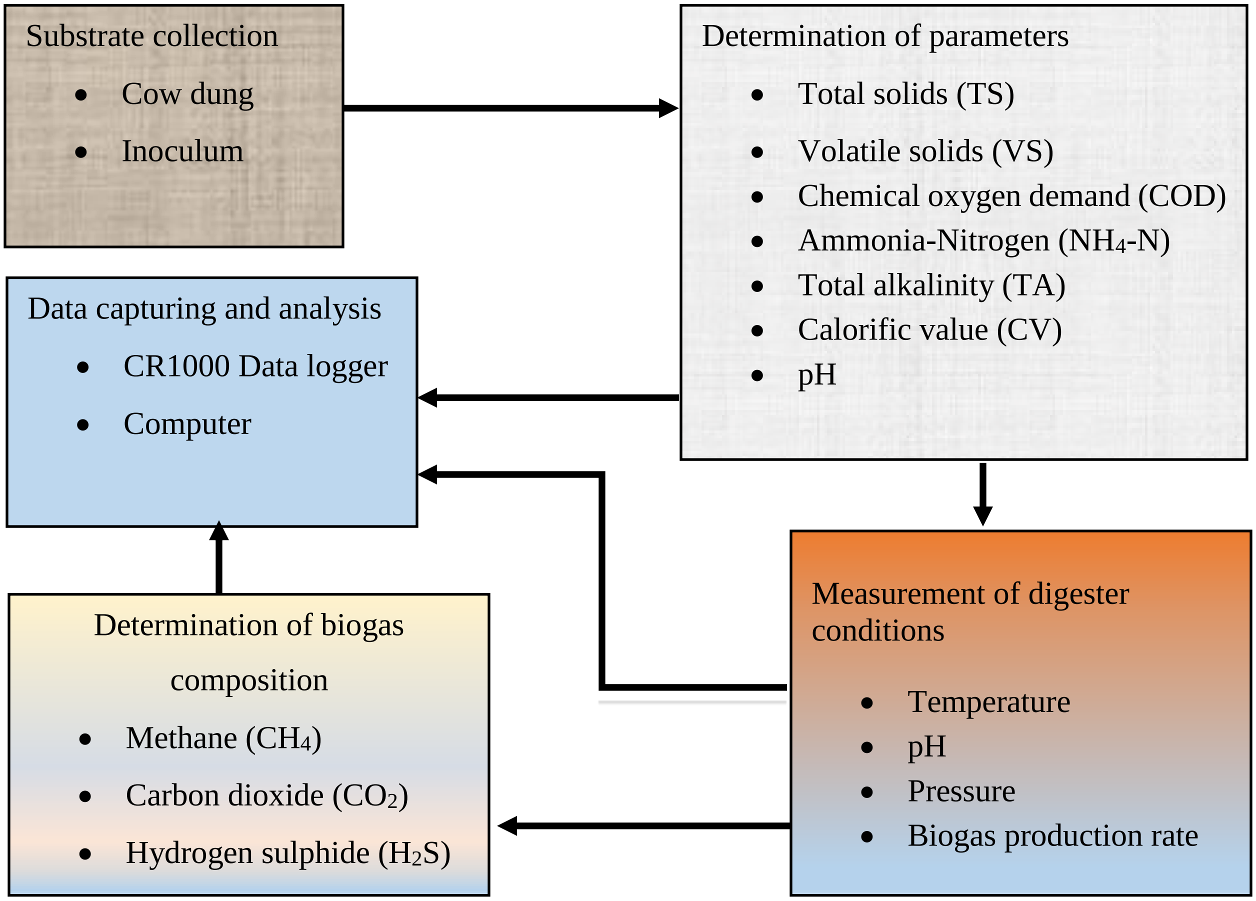

Figure 3.4: Digester performance evaluation flow chart

Cow dung was collected from the dairy farm at the University of Fort Hare. No inoculum was available to aid the digester start up, hence fresh dairy cow dung was used (Nasir, Omar, & Idris, 2013) to form an improved substrate, which produces biogas within a few days of feeding (Darwin, Cheng, Liu, Gontupil, & Kwon, 2014). Before being fed into the digester, the substrate was analysed for total solids (TS), volatile solids (VS), chemical oxygen demand (COD), ammonia-nitrogen ($NH_4$-N), total alkalinity (TA), calorific value (CV) and pH. A 11% total solids slurry of the substrate was made and fed into the digester as recommended for anaerobic digestion in the mesophilic temperature range (Mao, Feng, Wang, & Ren, 2015). The digester internal temperature, pH, and biogas production rate were monitored as the anaerobic digestion process progressed. The composition of methane ($CH_4$), carbon dioxide ($CO_2$) and hydrogen sulphide ($H_2S$) in the biogas was also determined and all the data collected was captured for analysis by a data logger and computer system.

### 3.4.1 Substrate physico-chemical analysis

The total solids and volatile solids were determined by use of an oven and mass balance while the calorific value was determined using a CAL2K bomb calorimeter. The rest of the substrate parameters were determined using the AL450 Aqualytic® photometer. More substrate parameter determinations in particular, COD and VS, were done on the effluent from a batch anaerobic digestion of the cow dung in order to evaluate the performance of the digester in relation to the destruction of the organic fraction of the substrate.

#### 3.4.1.1 Total Solids (TS)/dry matter

Total Solids (TS) is the weight of the dry matter remaining after elimination of the moisture content. It is defined by Standard Methods and EPA as the material residue left in a vessel after evaporation of a sample and its subsequent drying in an oven at 103 to 105°C for one hour (Aqualytic®, n.d.). TS helps in the determination of the amount of solvent to add to a substrate for efficient biogas production (Deepanraj, Sivasubramanian, & Jayaraj, 2015; Darwin et al., 2014). To determine the TS of a substrate, a sample of the substrate was weighed using digital weighing scales and put in a heat oven set at a temperature of 105 °C for 24 hours then reweighed (Zhang, Su, & Tan, 2013). The TS was then calculated using the equation:

$$TS(\%) = \frac{m_3 - m_1}{m_2 - m_1} \times 100 \qquad [3.1]$$

where:

$m_1$ - mass of crucible (g)

$m_2$ - mass of crucible and sample (g)

$m_3$ - mass of crucible plus residue after being heated (g)

### 3.4.1.2 Volatile Solids (VS)/ Organic dry matter

Volatile Solids (VS) is the weight of organic solids burned off when heated to about 550°C in a heat oven. It is the portion of dry matter which remains after elimination of the inorganic fraction (raw ashes). In anaerobic digestion, VS are important intermediate products used mainly by methanogenic bacteria to produce methane (Guo et al., 2017). To determine VS, dry matter was weighed and heated in a crucible for two hours at 550 ºC in a preheated oven. The residue was then cooled in a desiccator and weighed. The ignition, cooling, desiccating and weighing steps were repeated until the weight change went below 4%. The final weight was then recorded and the VS determined using the equation:

$$VS(\%) = \frac{m_4 - m_1}{m_3 - m_1} \times 100 \qquad [3.2]$$

where $m_4$ is mass (g) of crucible plus residue after heating at 550 °C

### 3.4.1.3 AL450 Aqualytic® photometer

The COD, $NH_4$-N, TA, CV and pH were determined using AL450 Aqualytic® photometer. This Aqualytic® brand photometer is a modern, mobile photometer for rapid, reliable waste and wastewater testing which offers a wide variety of pre-programmed methods based on the proven range of Aqualytic® tablet reagents, liquid reagents, tube tests and powder reagents (VARIO Powder Packs) and is highly suitable for the demands of modern waste and wastewater analysis (Aqualytic®, 2015). Being a microprocessor-controlled waterproof and solvent resistant photometer with an ergonomically designed touch-sensitive keypad and large format graphic display allowing users to also store their own methods, AL450 was quite convenient in the determination of the substrate parameters. The AL450 is a filter photometer using interference filters at 6 different wavelengths. The unique design of the optics allows the automatic selection of the required wavelength without any moving parts. This and the dual beam technology utilizing an internal reference channel, guarantees the highest accuracy. For portable use, the instrument operates with seven standard rechargeable batteries.

The AL450 photometer has a set of function keys and an LCD that provides the user interface. In performing the various analyses, these keys were used. Figure 3.5 shows the Aqualytic® AL450 photometer.

Figure 3.5: AL450 Aqualytic® photometer

The following section briefly describes the major function keys on the photometer (Aqualytic®, 2015).

ON/OFF: Switches the photometer On or Off

ESC: Returns to selection of methods or previous menu.

F1: Switches between the compact and the detailed list for method selection.

F2: Shows a list with available chemical species and corresponding ranges.

F3: Prints entire data set with date, time, code number, method and test result.

↵: Confirming

Mode: displays the menu of photometer settings and further functions

▲▼: Moving the cursor up or down

Store: Stores the displayed test result

ZERO: For performing Zero

TEST: For performing Test

🕘 Displaying date and time / user-countdown

### 3.4.1.4 Selecting a method on the photometer

To select a method, the mode button is pressed in order to open the menu of photometer settings and further functions from where the methods option is found. There are two ways to select the required method (Aqualytic®, 2015):

a) Enter the method-number directly, or

b) Press arrow keys to select the required method from the displayed list.

Then confirm with the confirming key.

### 3.4.1.5 The principle of photometry

When specific reagents are added, the substrate sample takes on a degree of coloration that is proportional to the concentration of the parameter being measured.

The photometer measures this coloration. When a light beam reflected by the mirror from the LED passes through the colored sample, energy with a specific wavelength is absorbed by the substrate. Figure 3.6 illustrates the principle of photometry.

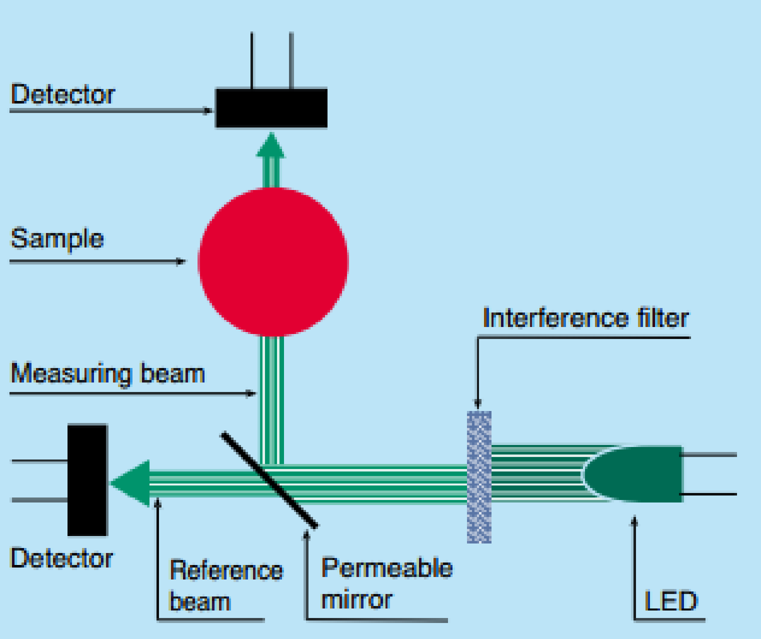

Figure 3.6: Aqualytic® general catalogue, 2010

The photometer determines the coloration of the sample by measuring the transmission or absorption of monochromatic light of this wavelength The photometer then uses a microprocessor to calculate the required concentration and displays the result (Aqualytic®, 2015).

#### 3.4.1.6 Chemical oxygen demand (COD)

The COD is a measurement of the amount of oxygen required to oxidize soluble and particulate organic matter in a given volume of substrate (Yao, Liu, Chen, Zhou, & Xie, 2015). To determine COD, a Vario tube test which measures COD within the range of 0 – 50 000 mg/l $O_2$ was used.

CSB Vario containing Dichromate/$H_2SO_4$ is the reagent used in the Vario tube test. The following procedure was followed in the determination of COD.

1. The adapter for 16 mm diameter reaction vials was inserted into the AL450 photometer.
2. 0.2 ml of de-ionised water were added to one white capped reaction vial (this is the blank vial).
3. 0.2 ml of substrate sample were added to another white capped reaction vial (this is the sample).
4. The vials were then closed tightly with the cap and gently inverted several times in order to mix the contents thoroughly. In the process of mixing the vial contents, the vials became hot and care was taken by use of a clean dry towel to avoid burning the hands.
5. The vials were then heated for 120 minutes in a preheated reactor at a temperature of 150°C in order to digest the vial contents. After heating, the vials were removed from the reactor and allowed to cool to 60°C before mixing the contents by carefully inverting each tube several times again while still warm and allowing them to cool further to ambient temperature.
6. The blank vial was placed in the sample chamber and the adapter cover put in place. Finger prints, foreign marks or any minor reagent residues can cause errors in the test result due to interference and thus a dry, clean towel was used each time to clean the vials, caps and stirring rods before placing them into the chamber.
7. The “zero” key was then pressed in order to set the photometer at zero absorbency.
8. The vial was then removed from the sample chamber.
9. Next, the sample vial was placed in the sample chamber gently to avoid the precipitate at the bottom of the sample from being suspended since suspended solids in the vial lead to incorrect measurements.

The COD result was then read from the display in g/L which was then converted to mg/L.

#### 3.4.1.7 pH

pH (potential of hydrogen), is a numeric scale ranging from 1 to 14 that is used to specify the acidity or basicity of an aqueous solution. A neutral pH is optimal for high biogas production (Deepanraj et al., 2015). For the determination of pH, two tests were carried out. One test was suitable for low range values of pH (5.2 – 6.8) and the other would measure a high pH range (8.0-9.6). The reagent used for the low range pH tests was a bromocresolpurple photometer tablet and for the high range pH tests a thymolblue photometer tablet was used. The procedure followed was as outlined below:

A clean 24 mm diameter vial was filled with 10 ml of substrate sample and closed tightly with the cap. The vial was then placed in the sample chamber and the zero key pressed. After removing the vial from the sample chamber, one tablet was added directly from the foil to the substrate sample and crushed using a clean stirring rod. The vial was then tightly closed with the cap and swirled several times gently until the tablet was dissolved in the substrate. Next, the vial was placed in the sample chamber and the test key pressed to display the result is as pH-value.

#### 3.4.1.8 Total alkalinity

Alkalinity is the buffering capacity of the digester. It is important in controlling the pH and in improving digester stability (Xue et al., 2017). An alka-m-photometer tablet 5 – 5000 mg/l $CaCO_3$ reagent was used. To determine the total alkalinity (TA), a clean 24 mm diameter vial was filled with 10 ml of substrate sample and closed tightly with the cap. The vial was placed in the sample chamber and the zero key pressed. An alka-m-photometer tablet was then added straight from the foil to the substrate and crushed using a clean stirring rod after taking out the vial from the sample chamber. The vial was then closed tightly with the cap and swirled several times until the tablet got dissolved. After placing the vial in the sample chamber the test key was pressed to display the total alkalinity result.

For accurate results about 10 ml of water sample must be taken for the test.

#### 3.4.1.9 Ammonium-Nitrogen

Biogas production from nitrogen-rich substrates can result in the release of ammonia ($NH_3$), which culminates in the inhibition of the microbial process. A threshold for stability in anaerobic processes was identified as being about 1 g $NH_3$-N $L^{-1}$ of substrate, irrespective of the organic loading rate (OLR) (Moestedt, Müller, Westerholm, & Schnürer, 2016). In this research, to determine $NH_3$-N, Ammonia 2 – 300 mg/l N Tablet reagent was used. A clean 24 mm diameter vial was filled with 10 ml of substrate sample, closed tightly with the cap and placed in the sample chamber. The zero key was then pressed and the vial taken out from the sample chamber. One ammonia No. 1 tablet was added from the foil to the sample and crushed using a clean stirring rod followed by one ammonia No. 2 tablet from a different foil to the same substrate sample and crushing of the tablet using a stirring rod. The vial was then closed and the tablets dissolved by gentle swirling of the vial. After placing the vial in the sample chamber, the test key was pressed a reaction period of 10 minutes was allowed after which the measurement started automatically leading to the result display in mg/L ammonia as nitrogen.

#### 3.4.1.10 Calorific value (CV)

The utilization of biomass derived biofuels requires the knowledge of their thermal properties, the calorific value being the most important of the thermal properties (Christoforou, Fokaides, & Kyriakides, 2014). The calorific value of a fuel is the amount of heat energy produced per unit weight or volume of the fuel during complete combustion (Christoforou et al., 2014). The Calorific value (CV) of the substrate was measured in MJ/g with a calorimeter (CAL2K) before the substrate was fed into the biogas digester. The calorimeter measures the heat of substrate (fuel) sample when burned under stable temperature conditions to evaluate the heating energy of the substrate. 10g of substrate was weighed in a mass balance and placed in a crucible and placed inside the stainless steel bomb vessel with a design pressure of up to 300 atm. Figure 3.7 shows the mass balance used to weigh the desired amount of substrate sample and Figure 3.8 shows the CAL2K vessel and its internal components.

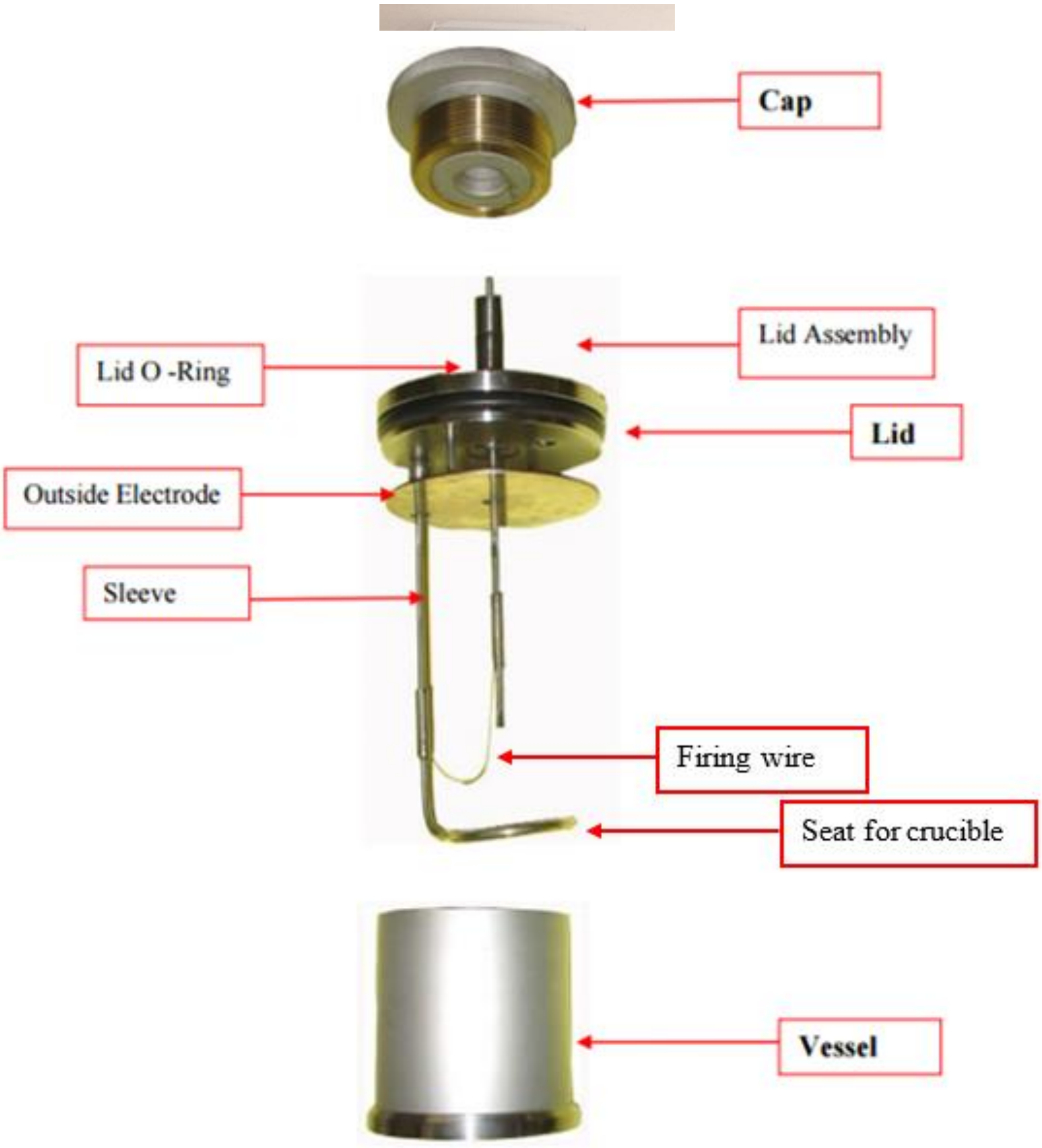

Figure 3.8: CAL2K vessel and internal components

The bomb vessel is designed in such a way that it is sealed and isolated from outside temperature influences. Once the bomb vessel temperature has stabilized in the bomb well, an electrical ignition charge instantly heats the ignition wire, which in turn burns the attached firing cotton thread. The burning cotton thread falls into the fuel sample leading to its ignition. This ignition is enhanced by the oxygen-rich environment within the vessel but however, in the case of an unsuccessful ignition, a report is given on the LCD display as a misfire so that the process can be aborted.

The bomb vessel was filled in with pure oxygen at a filling station to a pressure of 30 atm by use of a lever. Figure 3.9 shows the CAL2K filling station.

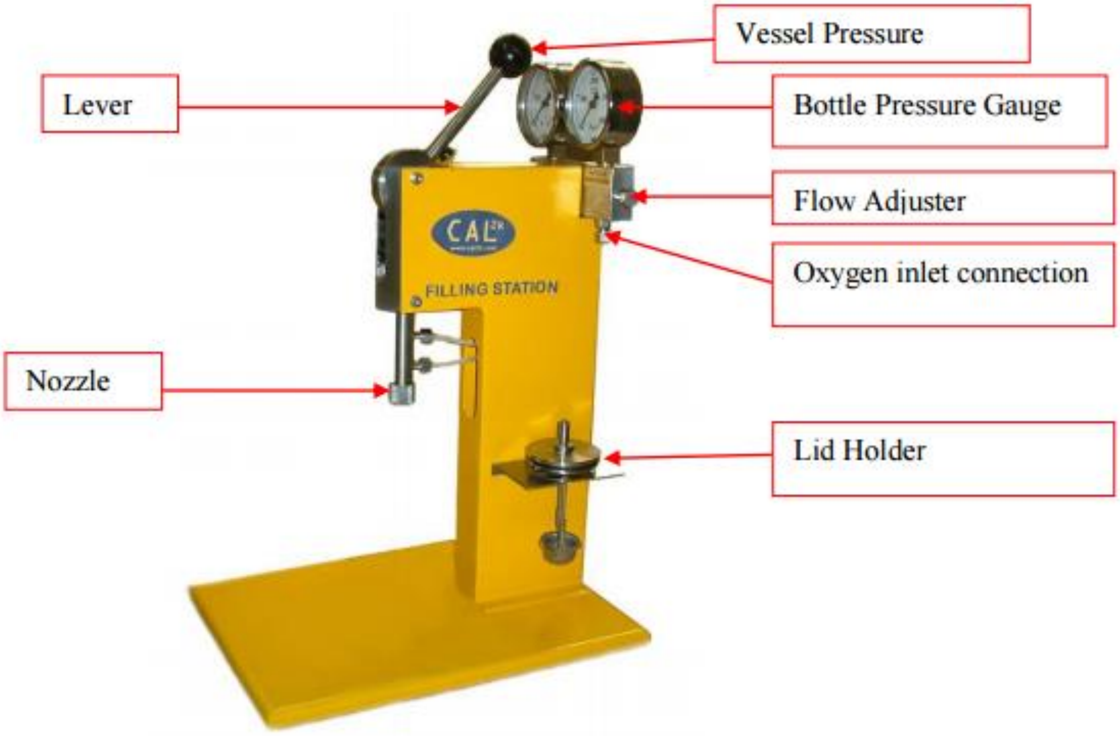

Figure 3.9: CAL2K Filling station

After this, the oxygen full bomb vessel was placed inside the calorimeter and the lid was closed. To accurately measure the temperature of the vessel, sensitive high resolution temperature sensors were used, measuring every 6 seconds for the duration of the determination. Once the determination was complete, typically within 4 minutes the calorimeter calculated the calorific value (CV) of the fuel sample and displayed it. After the determination of the CV of substrate, the bomb vessel was removed from the bomb well for cooling and reuse in the next determination. Figure 3.10 shows a closed calorimeter unit.

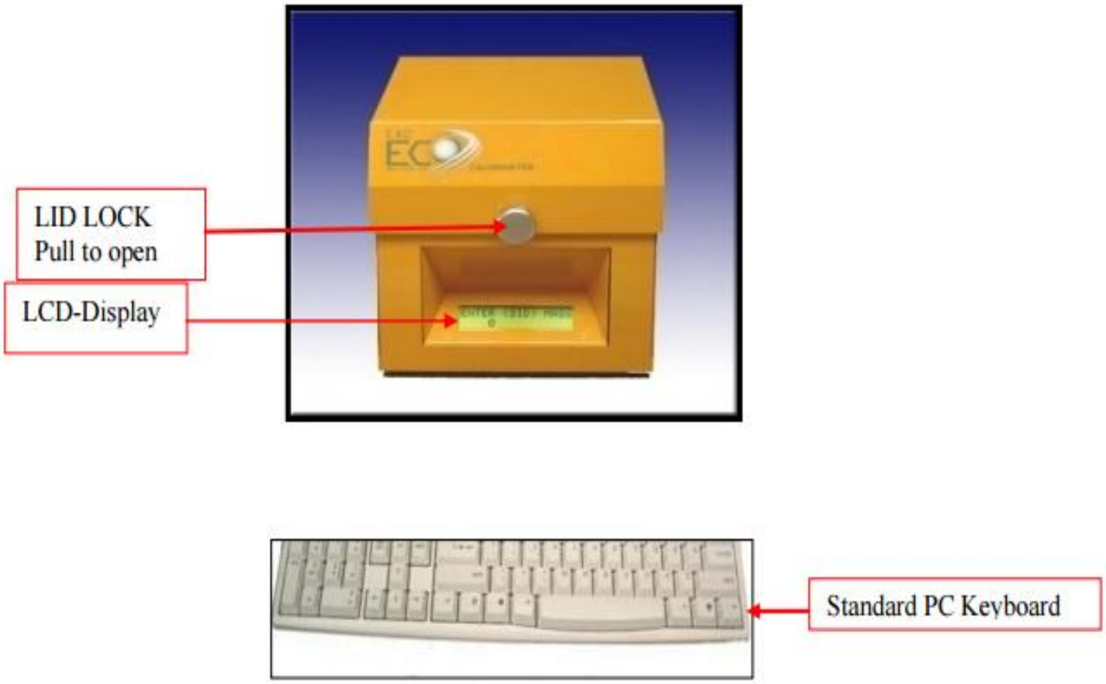

Figure 3.10: CAL2K calorimeter

### 3.4.2 Biogas volume and quality measurements

Biogas production rate was measured using a serial residential (SR) digital diaphragm type biogas flow meter. A biogas analyser was used to measure the biogas composition.

#### 3.4.2.1 Biogas production rate

The SR biogas flow meter is a positive displacement (PD) meter where the gas flows into the flow meter chamber which has an oscillating diaphragm and contains a known capacity of the gas through an inlet. The chamber section fills up with gas and empties the gas while with each cycle the volumetric flow rate is determined. This type of flow meter has the advantages that it is relatively inexpensive, corrosion resistant and has a long life expectancy. It however requires periodic maintenance and is more compatible with clean gas. Figure 3.11 shows the serial residential biogas flow meter that was used in the determination of biogas production rate.

Figure 3.11: Serial residential (SR) diaphragm biogas flow meter

#### 3.4.2.2 Biogas composition

For biogas composition, a SAZQ handheld biogas analyser which can detect methane ($CH_4$), carbon dioxide ($CO_2$) and hydrogen sulfide ($H_2S$) at the same time was used. The device uses the infrared optical principle to detect $CH_4$ and $CO_2$ gas concentrations using the wavelength characteristics of the gases. For the detection of $H_2S$, the electrochemical principle is used where the internal electrode reacts with the gas being detected in the role of catalyst to achieve the directional movement of electrons between the electrodes and make the electrical signal amplified and displayed by the amplification circuit technology so as to achieve the detection of concentration. The analyser gives the gas composition of the three gases mentioned above within the range of 0-100 % by volume for $CH_4$ and $CO_2$ within a response time of 70 seconds and 0-1000 ppm for $H_2S$ within 45 seconds. An alarm can be set to sound once a specified composition of a certain gas is reached. This is done by use of the four buttons on the interface which help in navigating between the normal gas detecting and the function interfaces. The battery of the analyser can be charged with a power supply voltage 110-240V and the analyser has a working temperature within the range of -25 -55$^{o}$C and is therefore very suitable for use in anaerobic digestion applications. To determine the composition of the biogas produced by the designed digester, the on/off button was long pressed to start the biogas analyser. This brought up the normal detecting interface on the LCD. After connecting the calibration mask to the biogas analyser and the air sampling pump via a connecting tube, the air sampling pump was connected to the biogas outlet on the flow meter and within 45 seconds, the composition of $CH_4$, $CO_2$ and $H_2S$ were displayed on the LCD of the analyser. This data was recorded and stored continuously on the analyser at 10-minute intervals and transferred through the USB cable from the analyser to the computer for analysis. Figure 3.12 shows the SAZQ biogas analyser.

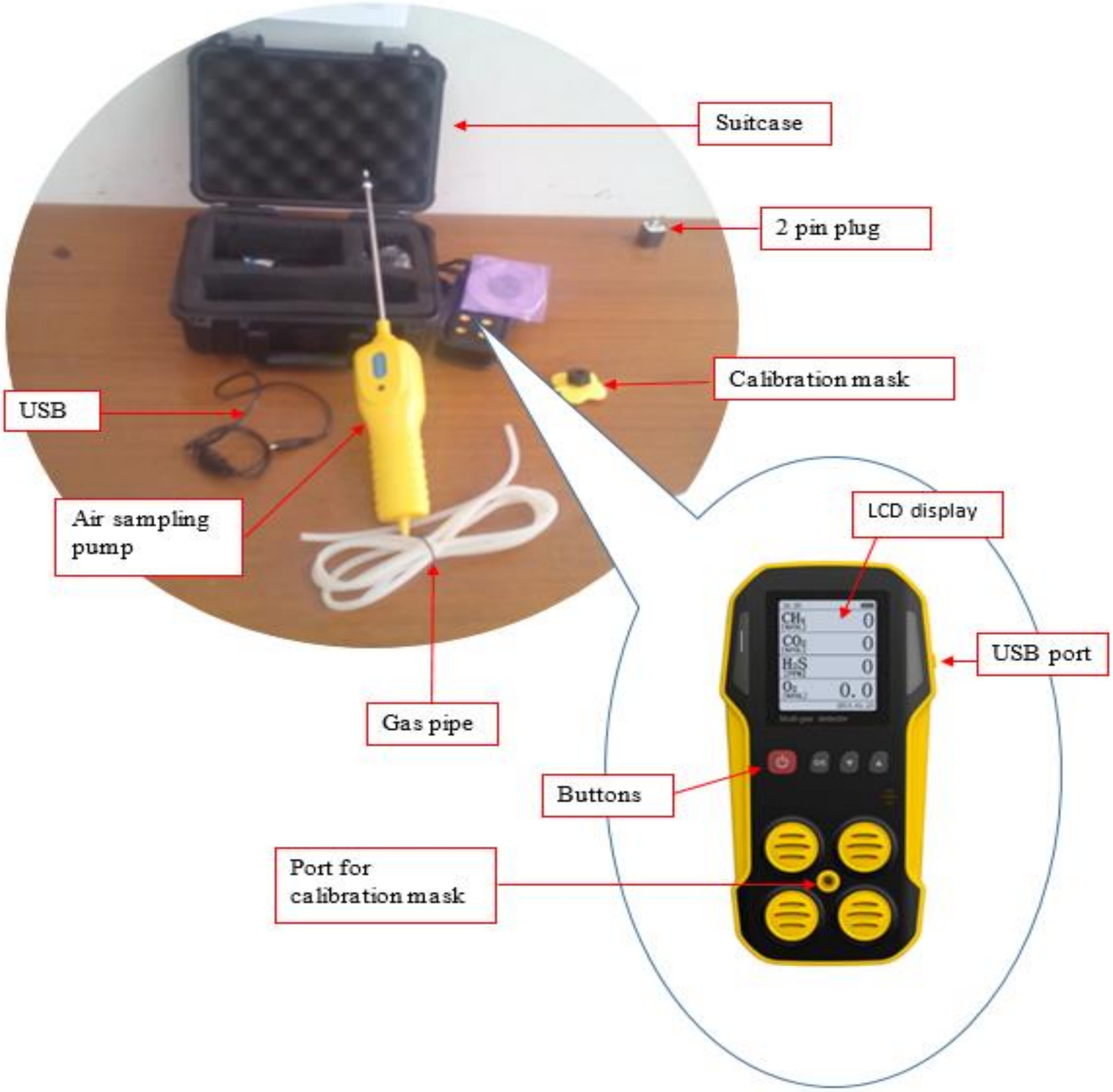

Figure 3.12: SAZQ biogas analyser

#### 3.4.2.3 Digester temperature and pressure

The digester temperature and pressure were measured using the pasport temperature and pressure sensor. Figure 3.13 shows the Pasport temperature and pressure sensor, PS-2125 probe and PS-2000 Xplorer used in the measurement and monitoring of the designed digester temperature and pressure.

Figure 3.13: Temperature and pressure sensor PS-2125 and PS-2000 Xplorer

This sensor measures temperatures within the range of -35 $^{o}$C -135$^{o}$C and has an accuracy of 0.01 $^{o}$C. When measuring liquid temperature, the device has a response time of 15 seconds within which readings become stable and when measuring the air temperature, it takes 30-60 seconds for the readings to stabilise. The sensor is attached on one end to a temperature probe made of steel hence suitable for use in liquids as it resists corrosion. At the same end of the sensor is connected a flexible gas pipe to measure the pressure at which the gas exits the digester. The other end of the sensor has a plug which is connected to a pasport link device (PS-2000 Xplorer). A USB connects the PS-2000 Xplorer to the computer and once the pasport sensor is detected, an EZscreen is launched by the EZscreen softaware. On this screen, the temperature and pressure can start to be recorded by clicking the Start button. The graphs of temperature and pressure against time can be plotted automatically fitting the current data and draging the cursor over the graphs displays the X,Y coordinates and gradients of the graphs as required.

## 3.5 SUMMARY

AutoCAD and TinyCAD computer software were used for the production of design drawings in 2D and 3D dimensional views. During the digester construction, metal sheet rolling was done using a single-pinch (initial-pinch) 3 roll bender roller which produces a cylindrical vessel shape. Metal cutting was done using a guillotine and a press was used in conjunction with a forming and pressure roller to produce a tori-spherical metallic bottom. Workshop tools such as the pliers, thin metal sheet cutter, rivet gun, saw, drilling and welding machines, screw driver, club and claw hammer, measuring tape, painting brushes, and vice grip were used for the construction of the greenhouse and all the digester fittings. The AL450 Aqualytic photometer which contains a variety of pre-programmed methods based on the proven range of Aqualytic® tablet reagents, liquid reagents, tube tests and powder reagents was used for the determination of the chemical oxygen demand, pH, total alkalinity and ammonia-nitrogen. A mass balance and an oven were used for the determination of total solids and volatile solids. The calorific value was determined using a CAL2K bomb calorimeter, mass balance and oven. Temperature measurements were done using a Pasport PS-2125 temperature sensor coupled with a PS-2000 Xplorer while biogas production and quality were determined by use of the Serial residential diaphragm biogas flow meter and the SAZQ biogas analyser respectively.

# CHAPTER 4: DIGESTER DESIGN AND CONSTRUCTION

## 4.1 INTRODUCTION

In this chapter, a 100-litre, temperature controlled, portable anaerobic biogas digester was designed. The design of the digester included the design specification and description and explanation of the proposed design for the digester which involves an agitated low-pressure vessel housed within a greenhouse structure. A comprehensive explanation of the heat-transfer processes and selection of materials for construction is also given.

## 4.2 BIO-DIGESTER DESIGN SPECIFICATIONS

Anaerobic digestion largely depends on the biological activity of relatively slowly reproducing methanogenic bacteria. These bacteria are greatly affected by temperature levels and fluctuations. Temperature control thus plays a very central role in the success of the methanation process though many small-scale biogas digesters in existence do not achieve satisfactory temperature control as revealed in chapter two. Efficient temperature control, agitation and design applicability in any setting are the major digester aspects not fully addressed. In this work, the design of the digester should therefore meet the following requirements:

- Maintenance of an economically feasible optimum operation temperature of $35 \pm 1^{o}$C within the mesophilic range with minimal temperature fluctuations
- Efficient and sufficient substrate agitation to enhance maximum biogas production and high methane yield
- Portability, which enhances digester applicability in any location regardless of the ground type and terrain
- Easy construction, operation and maintenance

## 4.3 SYSTEM DESCRIPTION OF THE PROPOSED DESIGN

In order to meet the stated specifications, an agitated portable biogas digester under greenhouse-regulated operation temperature design was done. Figure 4.1 is a schematic and Figure 4.2 shows a 3-dimensional view of the digester design.

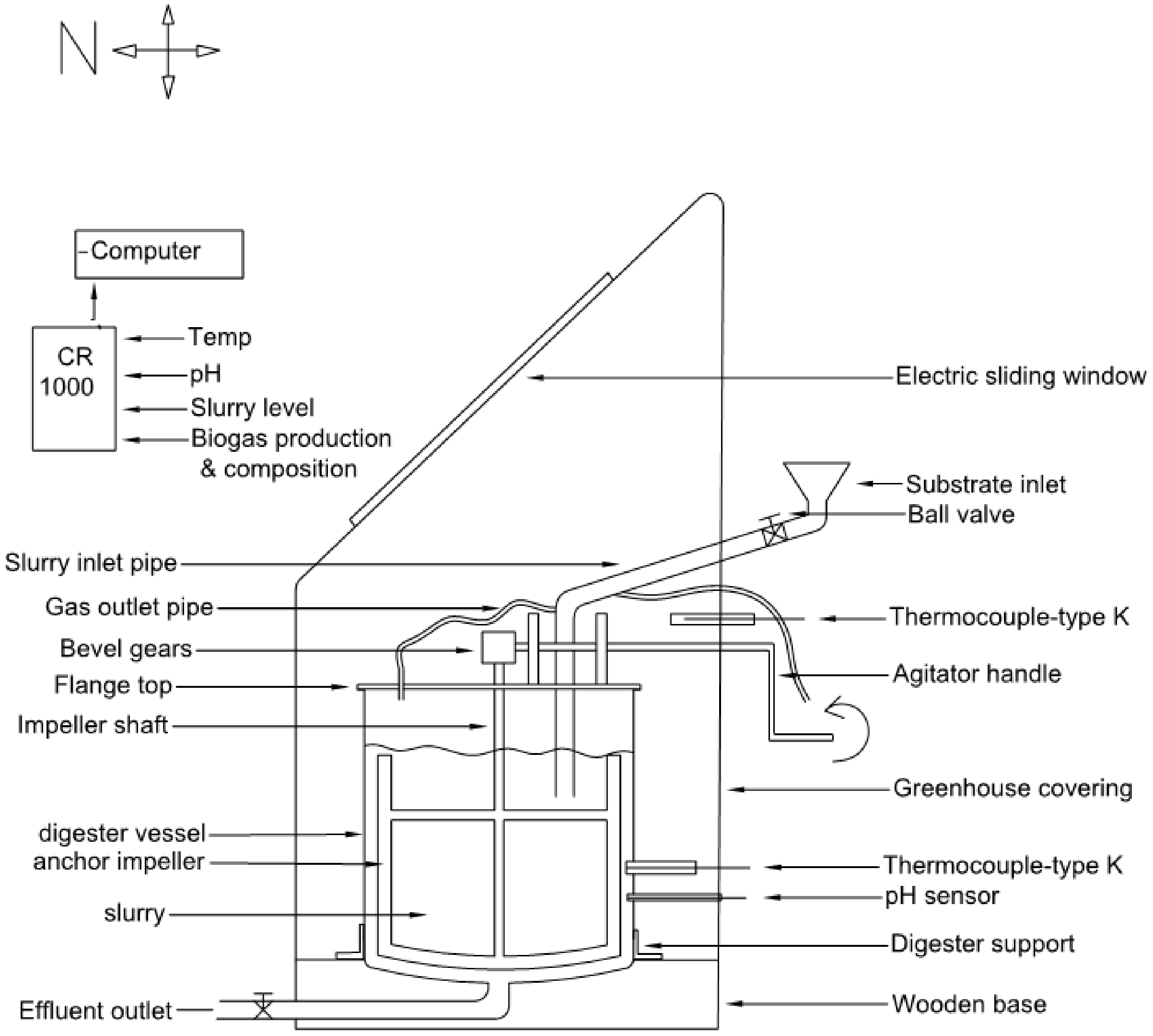

Figure 4.1: Schematic of the agitated portable digester under greenhouse-regulated temperature

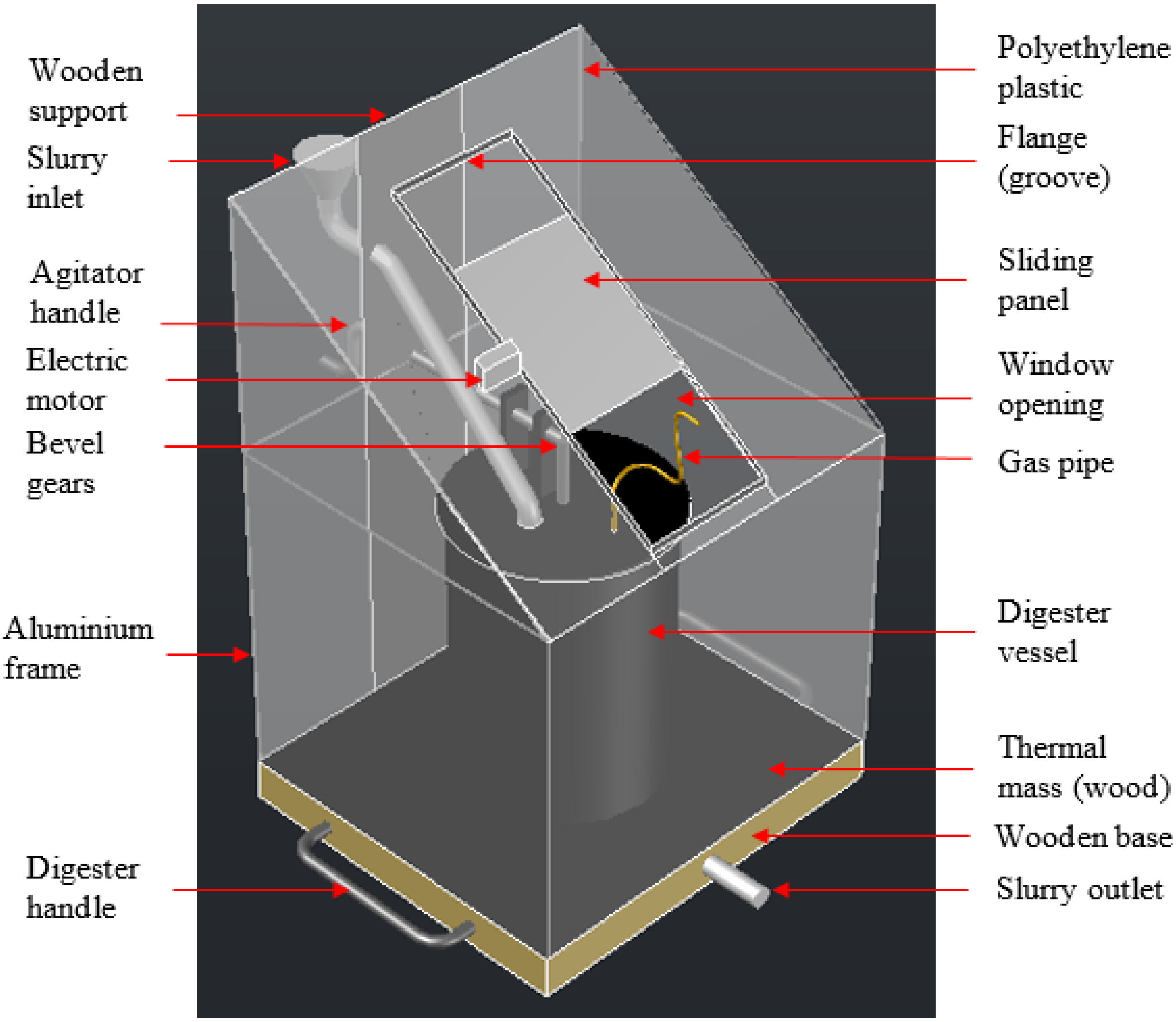

Figure 4.2: 3 – dimensional view of the proposed digester.

### 4.3.1 Digester operation

Through the substrate inlet, prepared substrate is fed into the digester vessel either semi-continuously or in batches for digestion. The quantity of substrate to be fed per day, for semi-continuous operation, is determined using equation 4.1. The daily substrate input quantity, $S_d$ is calculated from digester volume, $V_d$ and retention time, $t_R$:

$$V_d = S_d t_R \qquad [4.1]$$

At the elapse of the retention time, effluent is removed through the outlet at the bottom of the vessel. Ball valves at the inlet and outlet are closed during the digestion process so that the vessel is airtight. The digester organic loading rate, $L_r$ is calculated from the volatile solids quantity, $S_v$ and the digester volume, $V_d$:

$$L_r = \frac{S_v}{V_d\, t} \qquad [4.2]$$

where $t$ is time (days)

Intermittent agitation is done using an anchor impeller which is rotated manually from without the greenhouse. The daily biogas production, $G$ is calculated on the basis of the specific gas yield of the substrate under digestion, $G_y$ and volatile solids, $S_v$:

$$G = S_v G_y \qquad [4.3]$$

The biogas produced accumulates in the head space and is collected for storage and use through the flexible gas hose which is connected to a gas flow meter and analyser for the determination of biogas production rate and composition respectively.

### 4.3.2 Construction materials

The digester vessel was constructed using low carbon steel which has a high thermal conductivity of 54 W/mK to ensure a high rate of heat conduction from the vessel surroundings into the slurry. Mild steel was also used for the digester vessel and anchor impeller since it is cheap, easy to fabricate and weld, ductile and has high tensile strength. Though susceptible to corrosion, mild steel can still be used for anaerobic digester design when specially painted. Paints are used mainly for protection from atmospheric corrosion. NS5 METCOTE primer and Duram DTM black, an epoxy-based paint, were used to paint the digester vessel black for corrosion prevention and improved thermal absorption.

Low density polyethylene (LDPE) transparent plastic was used for the greenhouse cover because of its low cost, high flexibility, high shortwave radiation transmissivity, 60-80% (Table 2.3), water impermeability and impact resistance (Hinsley, 2015). The plastic used was UV-inhibited in order to increase resistance to wear due to UV radiation. The plastic was also IR absorbing (not transmissive to IR radiation) to ensure that the digester vessel would not radiate directly to the outside (cold) environment, but that radiation exchange would be between the inner surfaces (thermal mass and vessel wall) and the greenhouse cover which is warmer than the outside environment, a condition which reduces the temperature gradient hence reducing radiative heat losses since the rate of heat transfer by radiative means $Q_r$, is directly proportional to and largely dependent on the temperature difference between the radiating and receiving body temperatures, $T_1$ and $T_2$ respectively as shown in equation [4.4]..

$$Q_r = \varepsilon \sigma A\left(T_1^4 - T_2^4\right) \qquad [4.4]$$

For insulation, a double layer of the polyethylene plastic trapping an air film in-between was used since air is a very good insulator with a thermal conductivity as low as 0.027 W/mK (Table 4.1). A wooden base was used since it is suitably rigid, cheap and has good insulation properties to keep heat within the greenhouse according to equation [2.8]:

$$Q_{cond-conv,a-e} = c_{cond-conv,a-e}\left(T_a - D_{T,e}\right),$$

which suggests that the rate of heat loss by conductive means, $Q_{cond-conv,a-e}$ from the air inside the greenhouse to the atmosphere is directly proportional to the heat transfer co-efficient, $c_{cond-conv,a-e}$ of the material through which the heat is being lost. Table 4.1: shows the thickness and thermal conductivity data for polyethylene plastic and air.

Table 4.1: Thickness and thermal conductivity data for polyethylene plastic and air (Green, 1990).

| **Material** | **Thickness, x (m)** | **Thermal conductivity, k (W/mK)** |
|---|---|---|
| *Plastic* | 0.0002 | 0.45 |
| *Air* | 0.005 | 0.027 |

The polyethylene plastic was hanging on aluminum flat bar frames. Aluminium was used since it is flexible, durable, affordable, and long lasting. It is a versatile metal, able to conform to various shapes and thicknesses, and can be moulded into the desired framing structures.

Heat losses by infiltration were minimised by ensuring a tightly constructed (air tight) greenhouse in accordance with equations [2.9]:

$$Q_{vent,a-e} + Q_{\inf,a-e} = \frac{c_{\rho,a} c_{p,a}}{c_{area,b}} V_{vent,\,flux} \left( T_a - D_{T,e} \right)$$

and [2.10]:

$$V_{vent,\,flux} = c_{vent,n} c_{vent,l} c_{vent,w} D_{ws,e} \left( \alpha_v U_{vent}^{\beta v} \right) + V_{loss}$$

which suggest that the amount of heat lost through infiltration is directly proportional to the size of small openings and the volume of the air escaping.

The inlet and outlet nozzle pipes were made of PVC and the gas outlet pipe was made of acid resistant rubber.

### 4.3.3 Digester vessel

The 100-litre digester vessel was designed to have three sections: a cylindrical section, tori-spherical bottom and flat plate flange top. For efficient agitation, prevention of dead zone formation, easy draining and hence maintenance of digester volume and prevention of corrosion respectively, the digester vessel bottom was made to be rounded (Coulson and Richardson, 2003). The flange was bolted to the cylindrical section with a nitrile rubber gasket in-between. This was done in order to enhance easy maintenance when need arises. The nitrile rubber gasket ensures an airtight enclosed volume within the digester vessel and being corrosion resistant, it is suitable for the anaerobic digestion application (Rowse, 2011). A tori-spherical bottom was chosen because it is relatively cheaper and easier to fabricate than the other rounded head types. A flat plate flange top was chosen because it’s the easiest and cheapest to fabricate (R.S. Khurmi J.K. Gupta, 2005).

Two type-K thermocouples were used to monitor the slurry temperature and the temperature of the air within the greenhouse. A pressure sensor was used to monitor the pressure within the digester vessel. Samples of the slurry were to be collected through the effluent outlet nozzle for the determination of COD, pH, TS and VS as required since the slurry conditions are uniform throughout the volume of the vessel due to efficient agitation.

Table 4.2 shows the data used in the calculation of the thickness of the three digester vessel sections.

Table 4.2: Low pressure vessel design parameters

| **Parameter** | **value** |
|---|---|
| Internal diameter, $D_i$ | 500 mm |
| Crown radius of tori-spherical bottom, $R_c$ | 500 mm |
| Knuckle radius of the tori-spherical bottom, $R_k$ | 50 mm |
| Working pressure, $P_i$ | 0.150 N/mm$^2$ |
| Design stress, $f$ | 135 N/mm$^2$ (Coulson and Richardson, 2003) |
| Joint factor, $J$ | 1.0 (no joints) (Coulson and Richardson, 2003) |
| Stress concentration factor, $C_s$ | 3.25 (from eqn 3.11) |
| Corrosion allowance | 2 mm (Coulson and Richardson, 2003) |
| Edge support coefficient for bolted flange tops, $C_p$ | 0.56 (R.S. Khurmi J.K. Gupta, 2005) |

#### 4.3.3.1 Cylindrical section thickness

A design pressure, $P_i$ within 5 - 15% above the normal working pressure was used to avoid spurious operation during minor process upsets (Khurmi and Gupta, 2005). Choosing a working pressure of 150 kPa and a design pressure, 15% above the working pressure, equation [2.18]:

$$t_c = \frac{P_i D_i}{2f - P_i} = 0.28\, mm.$$

To cater for corrosion, a corrosion allowance of 2 mm was added, leading to a vessel wall thickness of 2.28 mm. A standard 2mm thick carbon steel sheet was therefore used.

#### 4.3.3.2 Tori-spherical bottom thickness

Substituting the above data into equation [2.20]:

$$t_t = \frac{P_i R_c C_s}{2fJ + P_i(C_s - 0.2)} = 0.9\ mm.$$

Therefore, with a corrosion allowance, the thickness of the tori-spherical bottom was 2.9 mm and a standard thickness of 3.0 mm was used.

#### 4.3.3.3 Flat top flange

Using equation [2.19]:

$$t_f = C_p D_i \sqrt{\frac{P_i}{f}} = 9.3\ mm.$$

With a corrosion allowance, the thickness becomes 11.3 mm and a standard plate thickness of 12.0 mm was used.

Figures 4.3 and 4.4 show the digester vessel and impeller cross-sectional dimensions and the digester vessel plan view respectively.

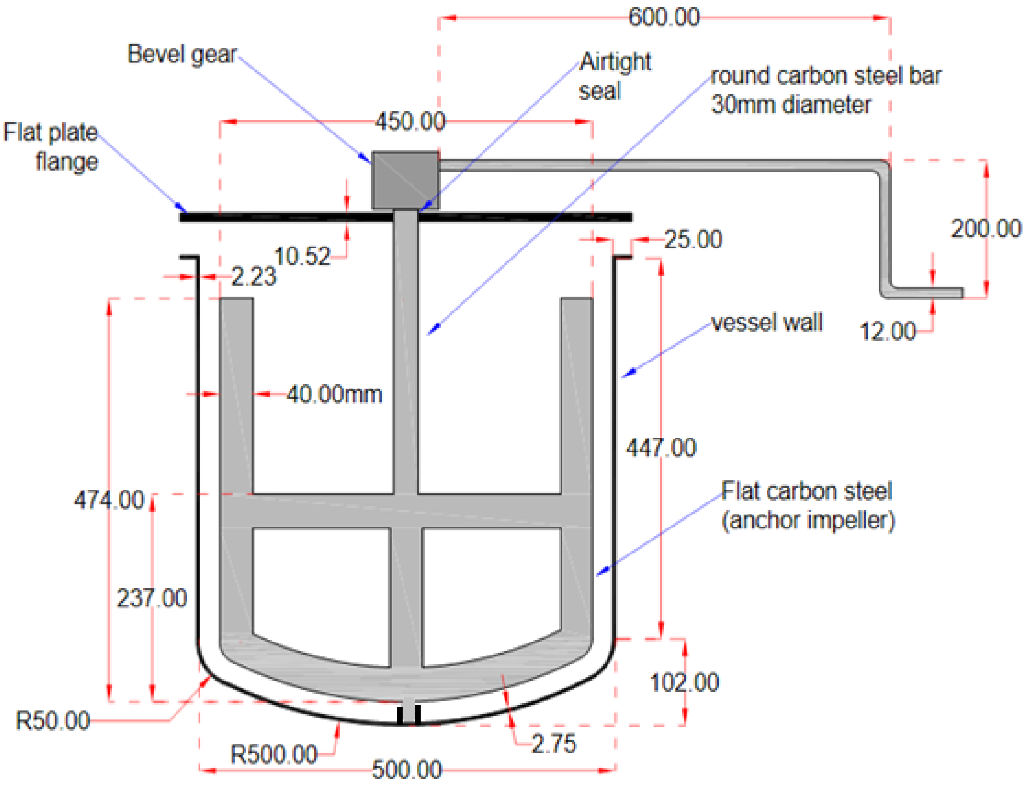

Figure 4.3: Digester vessel and impeller dimensions (mm)

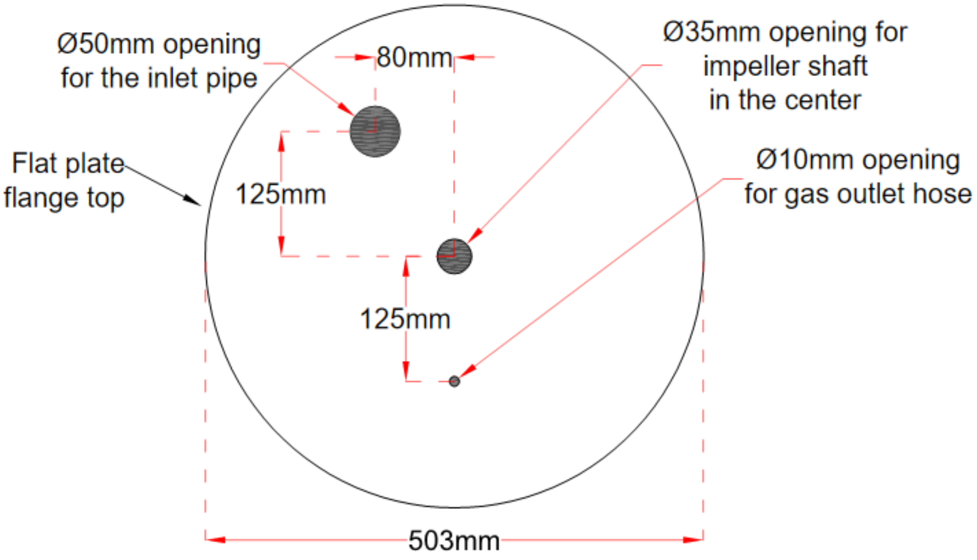

Figure 4.4: Digester vessel plan view

### 4.3.4 Greenhouse

The greenhouse volume was designed to be large enough to house the digester vessel and all the fittings on it. Figure 4.5 is the front, side and top elevations and dimensions of the greenhouse that was constructed.

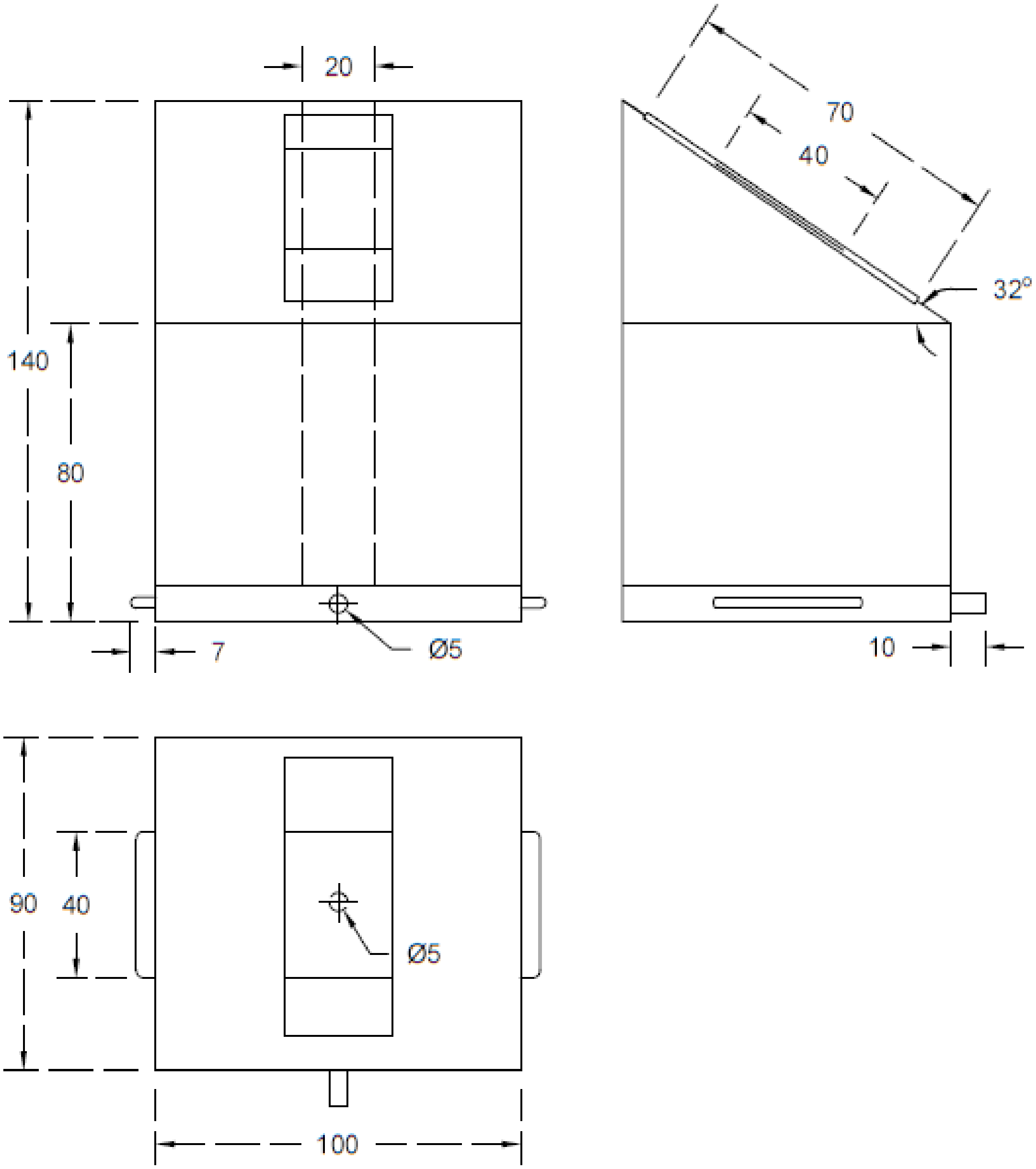

Figure 4.5: Greenhouse dimensions (cm)

### 4.3.5 Digester temperature control

In order to heat the digester to 35$^{o}$C, short wave solar irradiation which is mainly ultraviolet (UV) radiation, is transmitted through the double layer of polyethylene plastic into the greenhouse structure. For maximum direct transmission, the greenhouse north-facing top side was constructed at a tilt angle of 32$^{o}$, which is the latitude of the University of Fort Hare lying in the southern hemisphere, where the design was done. This shape also increases the surface area for solar radiation transmission. Diffuse radiation transmits into the greenhouse through the greenhouse cover from any direction. The fraction of radiation transmitted into the greenhouse through the plastic is absorbed by the mild steel digester vessel wall painted black and a fraction of it by the wooden greenhouse floor (base). The absorbed radiation is converted to thermal energy, a fraction of which is conducted through the digester vessel wall into the slurry, thus raising the slurry temperature. The unabsorbed fraction is re-radiated into the greenhouse as long wave low frequency thermal (IR). This thermal radiation is trapped within the greenhouse since it cannot be transmitted through the polyethylene plastic into the atmosphere. This results in a build-up of heat energy within the greenhouse and slurry. A rise in temperature within the greenhouse structure and consequently the slurry is therefore achieved this way till the desired optimum temperature of 35$^{o}$C is reached.

In case of excess heat (above 35$^{o}$C) within the greenhouse, warm air is vented out and replaced with cool air from the outside environment by convectional means. The venting of warm air is achieved by an automatic electric sliding window on the greenhouse.

A 12VDC temperature relay switch actuates a 12V direct current (D.C) motor to slide the window open once the set point temperature of 35 $^{o}$C is reached. The motor is stopped by means of a double throw normally closed (NC) limit switch (Top limit switch) placed in the way of the sliding pane within the groove at the top extreme of the window frame (refer to Figure 4.2), once there is physical contact between the sliding window and the switch. This stops the flow of current through the motor in this direction. Once the temperature goes below the set point, the relay switch actuates the motor to turn in the opposite direction hence closing the window. A bottom NC limit switch stops the window once it completely closes. The motor and window are attached by a gear interlocked with a rack.

The switching of directions in which the motor runs is made possible by an H-bridge circuit which controls the direction of the motor and to also provides enough current for the motor to run. Figure 4.6 shows the H-bridge circuit with S1-S4 representing switches 1-4 respectively and M representing the electric bi-directional motor. Vin is the supply voltage.

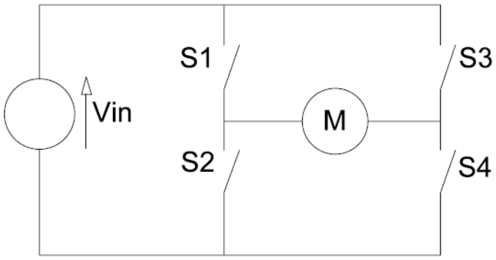

Figure 4.6: H-bridge circuit

An L6203 H-bridge integrated circuit (I.C) was used for the motor direction control since it combines isolated double-diffused metal oxide semiconductor (DMOS) power transistors with complementary metal oxide semiconductor (CMOS) and bipolar circuits on the same chip. By using this mixed technology it optimises the logic circuitry and the power stage to achieve the best performance. The DMOS output transistors can operate efficiently at high switching speeds. All the logic inputs are time-to-live (TTL), CMOS and mC compatible. Each channel (half-bridge) of the device is controlled by a separate logic input, while a common enable controls both channels. The L6203 is used in conjunction with the L6506 I.C which senses and controls the current in the load windings.

The temperature relay switch used is an On/Off Controller. This was selected above other controller types such as the proportional (P), proportional integral (PI), proportional derivative (PD), proportional, integral and derivative (PID) and fuzzy logic controllers due to cheap cost, simplicity and easy design and implementation. On/Off control was particularly used in this research since there was no need for very precise temperature control as temperature deviation from the optimum within the mesophilic range by 2-3°C does not affect microbial activity as highlighted in chapter 2. The On/Off control system is also very suitable for slow changing systems such as the slurry temperature which slowly changes due to the high heat capacity of the slurry (Aquarius Technologies, 2011; www.omega.com, n.d.).

When the temperature of the air within the greenhouse is below 35°C the temperature relay switch is Off and it turns On when the sensed temperature crosses 35°C. This drives the electric motor in such a direction as to open the sliding window. As temperature goes down again, crossing the set-point, the relay switch turns the Off. Since the output is On above 35°C and Off below 35°C, there is a continual cycling between On and Off since the temperature of the air within the greenhouse is fluctuates. This cycling would damage the electric motor and switches therefore an On-Off differential (hysteresis) is added such that the greenhouse air temperature must exceed the set point, 35°C by a predefined amount (hysteresis) of 2°C before the output will turn ON or Off. This prevents the output from making continual switches if the cycling above and below the set point occurs rapidly. Figure 4.7 shows the graph of the On/Off temperature control system with hysteresis, used for the digester temperature control.

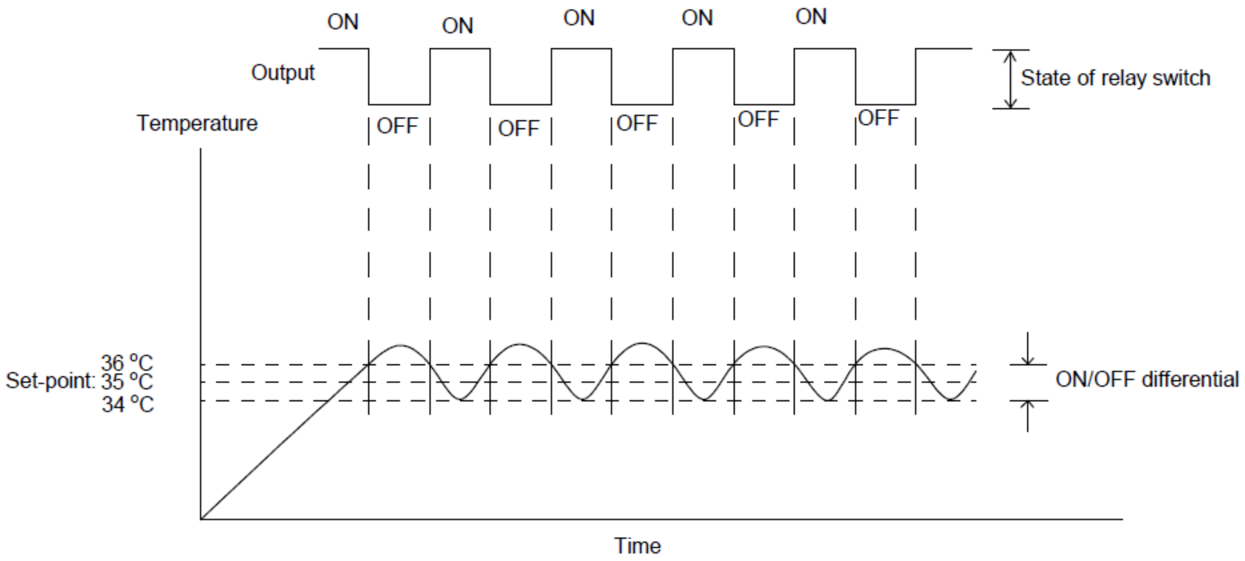

Figure 4.7: On/Off digester temperature control system with 2°C hysteresis

The electric motor speed can be adjusted by a potentiometer and the temperature set-point can also be adjusted using another potentiometer. For voltage supply, a 12VDC battery was used. This would directly supply the 12V temperature relay switch and L6203 integrated circuit. An L7805 voltage regulator controlled voltage supply to the 5VDC L6506 integrated circuit so that the whole control circuit was supplied by one source. Figure 4.8 shows the circuit diagram for the sliding window control to effect ventilation. The boxed components make up the temperature relay switch.

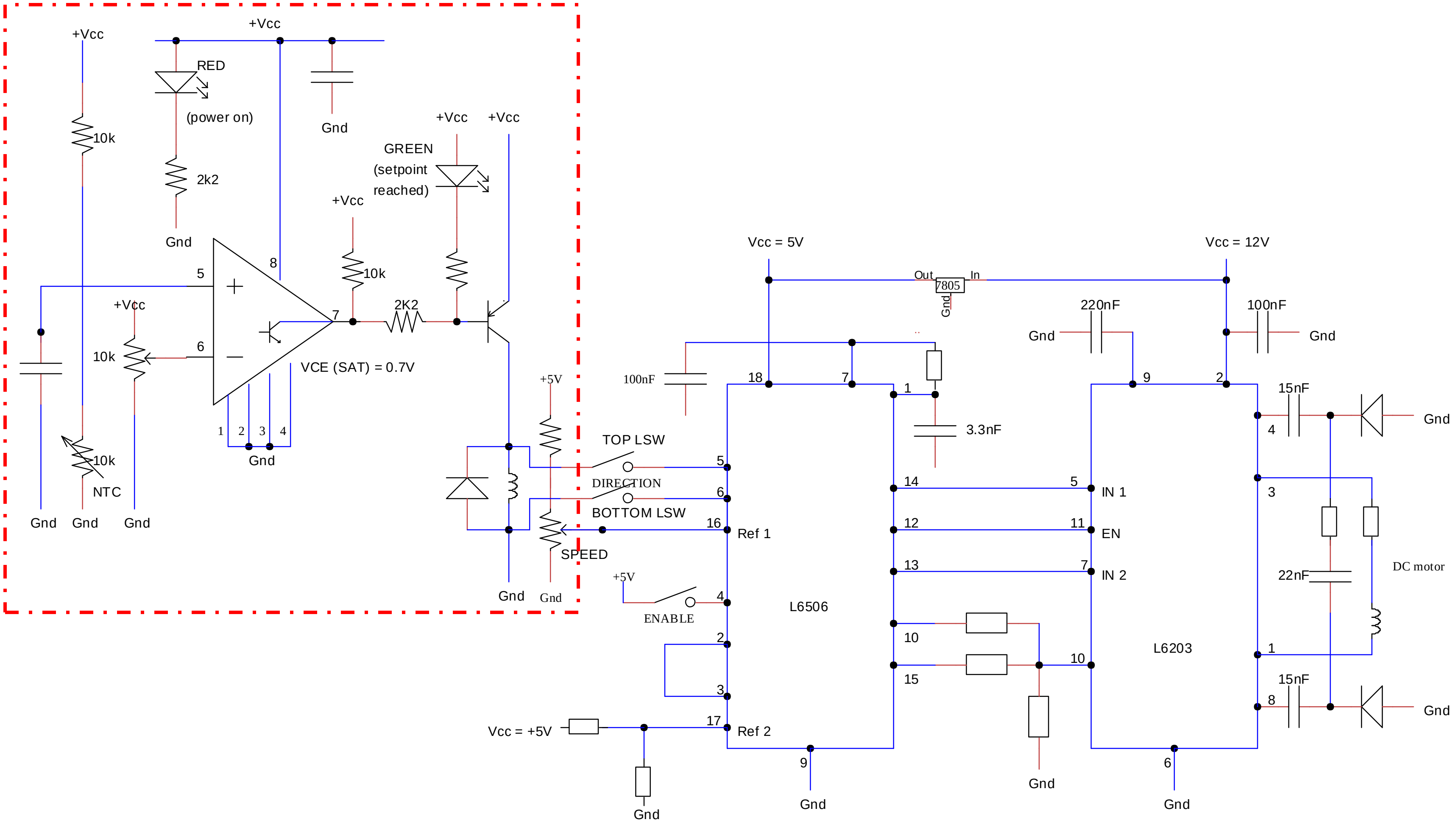

Figure 4.8: Circuit diagram for ventilation control

### 4.3.6 Digester agitation

For agitation, an anchor impeller was designed, because it is the impeller type that prevents the sticking of pasty materials onto the digester wall, due to the ratio of its width to the vessel width. This promotes good heat transfer from the wall to the bulk of the substrate slurry (Rabiner & Gold, 1985). The anchor impeller is also suitable for use in stirring fluids of high density such as slurries and pastes. Being a manually driven agitator, the anchor impeller is a cheap and attractive option. Substrate slurry mixing is done intermittently between 3 – 4 times per day depending on specific biogas digester size, feedstock quality and tendency to form a floating layer (Seadi et al., 2008). Slow and gentle agitation is achieved by manual stirring intermittently after feeding. The anchor impeller is rotated in a horizontal axis using a stirring shaft turned in a vertical axis. A bevel gear was used to shift the plane of rotation from vertical to horizontal. Two equations; [4.5] and [4.6] were used to determine the impeller dimensions relative to the digester vessel geometry. A round iron bar connects to the bevel gear, which rotates the impeller in a horizontal plane.

$$\frac{D_a}{D_i} = 0.95 \qquad [4.5]$$

$$\frac{H}{D_i} = 1 \qquad [4.6]$$

where:

$D_a$ - impeller diameter, $D_t$ - tank diameter, $H$ - slurry column height.

The tank diameter is 500 mm therefore the impeller diameter is 475 mm according to equation [4.5]. The gas tight seal for the impeller shaft comprises a ring shaped housing with a circular opening through which the shaft passes. The inner surface of the housing or the outer surface of the shaft is provided with two oppositely wound spiral grooves. At least one annular groove is arranged between the spiral grooves. The spiral grooves are wound in directions such as to ensure transport of gas away from the annular groove when the shaft rotates in normal direction

### 4.3.7 Digester portability

The digester unit was made portable by fitting handles on it for easy transportation. Portability also provides convenience when the need to move the digester to a point with higher solar irradiance arises. A rigid base and frames to support the vessel weight and the greenhouse covering respectively, were used.

## 4.4 DIGESTER CONSTRUCTION

### 4.4.1 Digester vessel

The construction of the designed biogas digester was done in a workshop at the University of Fort Hare. Figure 4.9 shows the fabricated digester vessel and the flat top flange with 3 openings for substrate inlet, gas outlet and agitator shaft.

Figure 4.9: Fabricated digester vessel (left) and top (right)

Three supports with holes for allowing the vessel to be bolted to a surface were welded, equidistanced around the circumference of the base of the vessel. The impeller was fitted in through the shaft opening together with its shaft seal and the bevel gears put in place as shown in Figure 4.10.

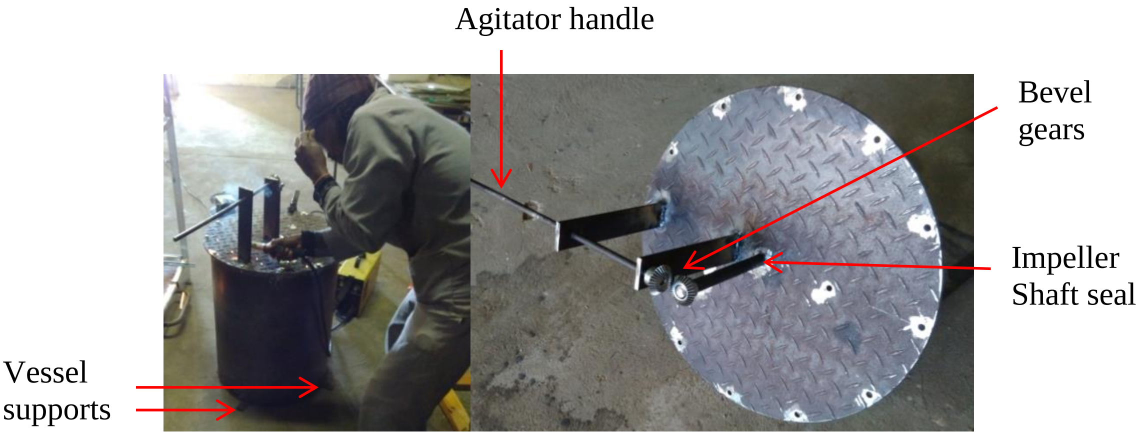

Figure 4.10: Agitator

PVC slurry inlet and outlet pipes and gas outlet pipe were fitted into the digester vessel. For a strong bond between metal and plastic, an epoxy glue mix was applied as shown in Figure 4.11.

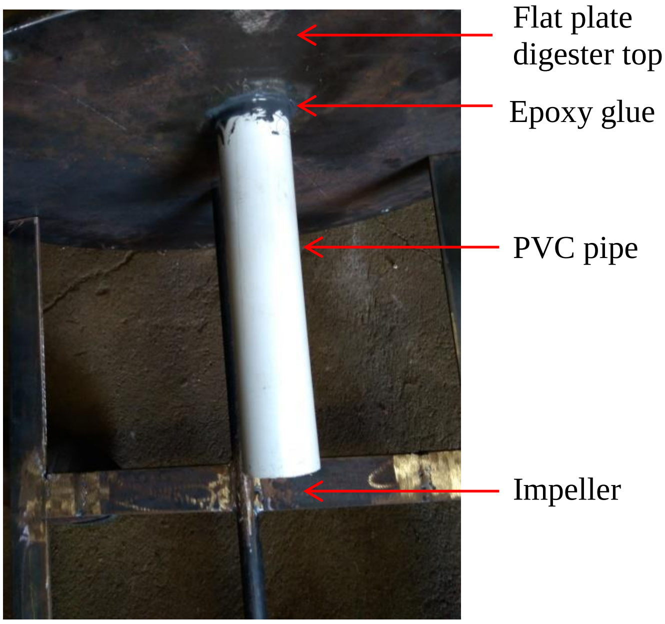

Figure 4.11: PVC pipe glued to metal surface

### 4.4.2 Greenhouse

A wooden base for the greenhouse was constructed using a saw, measuring tape, claw harmmer and iron nails. Iron bar handles taken from broken chairs were fitted to the wooden base as shown in Figure 4.12 using some metal clamps.

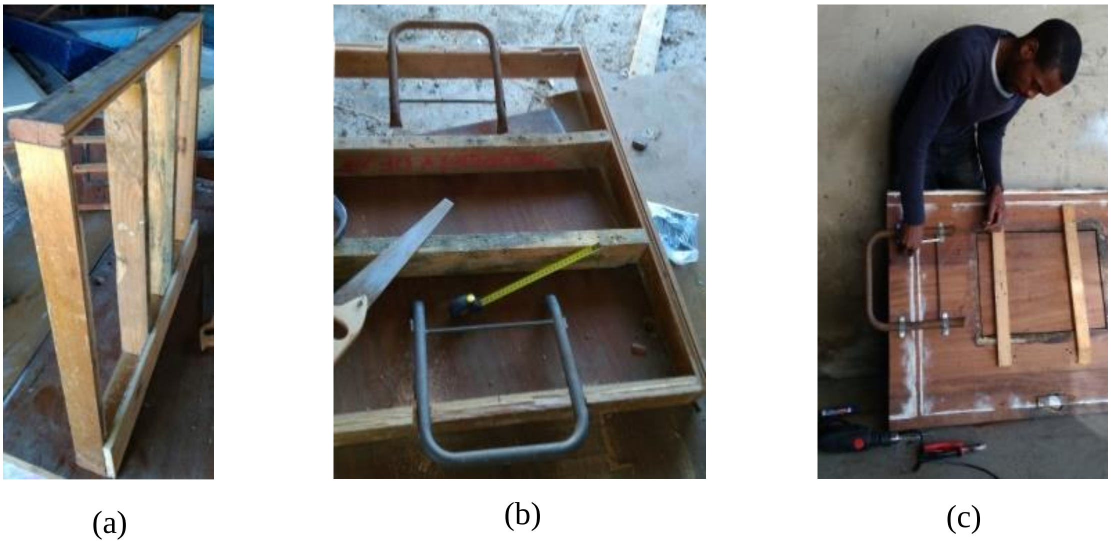

Figure 4.12: Greenhouse wooden base with metal handles

An aluminium frame was constructed using a vice grip and measuring tape and to hold the greenhouse plastic, a zig-zag (wiggle) wire profile was riveted to the aluminium frame and wooden base along the edges of the greenhouse where the plastic would be attached. Two openings were drilled in the wood for the slurry outlet pipe. Figure 4.13 shows the greenhouse framework and Figure 4.14 shows the rivet type used.

Figure 4.13: Greenhouse frame

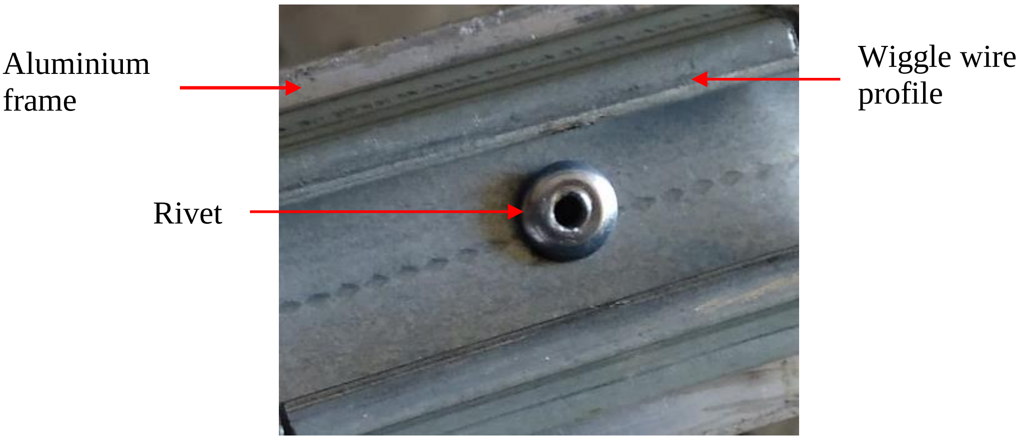

Figure 4.14: Riveted wiggle wire profile

The Sides of the wooden parts of the greenhouse that would be exposed to the weather conditions outside the greenhouse were covered with a thin iron metal sheet for protection from adverse weather conditions as shown in Figure 4.15.

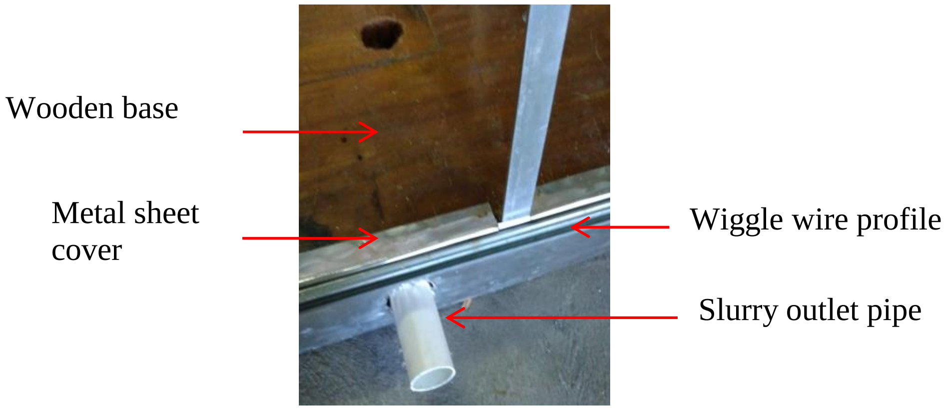

Figure 4.15: Metal sheet covering of wooden edge

The fabricated digester vessel was painted black and bolted to the wooden base of the greenhouse which was also painted black. The slurry outlet pipe connected to the base of the vessel ran through the wooden base to the side of the wooden base and the slurry inlet pipe, gas pipe and agitator handle ran through holes drilled through a vertical wooden support also painted black. Figure 4.16 shows the digester vessel fitted into the greenhouse frame.

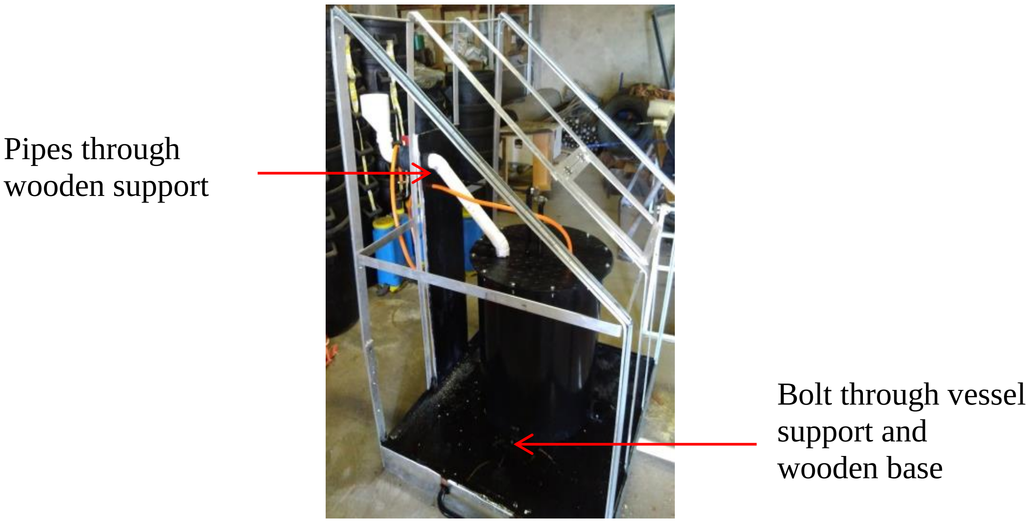

Figure 4.16: Digester vessel in greenhouse frame

The double layer polyethylene plastic was put over the greenhouse frame and clipped into the wiggle wire profile by a wiggle wire to cover the greenhouse. Figure 4.17 shows the digester (vessel in greenhouse) front and back South West (SW) isometric views.

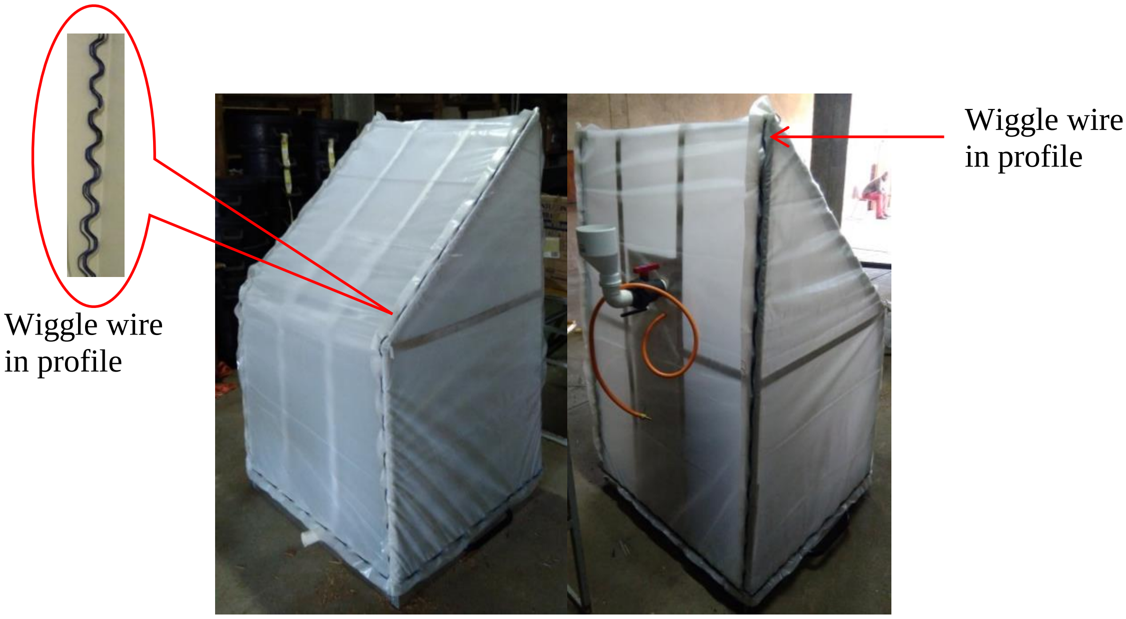

Figure 4.17: Digester front (left) and back (right) SW isometric view

### 4.4.3 Automatic temperature control system

After putting the greenhouse plastic, the window area was cut out and a sliding window shown in Figure 4.18 was constructed for temperature control. The window had a PVC sliding pane, wooden frame and electric motor covered by a thin metal sheet.

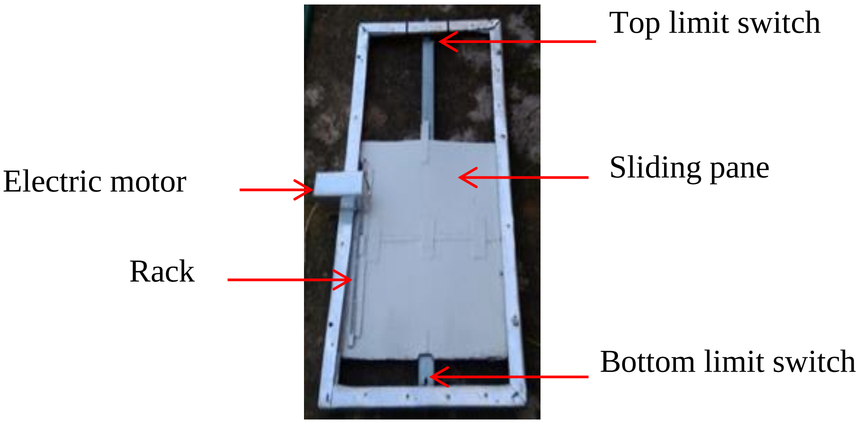

Figure 4.18: Electric sliding window

Figure 4.19 shows the electric motor and rack on the sliding pane.

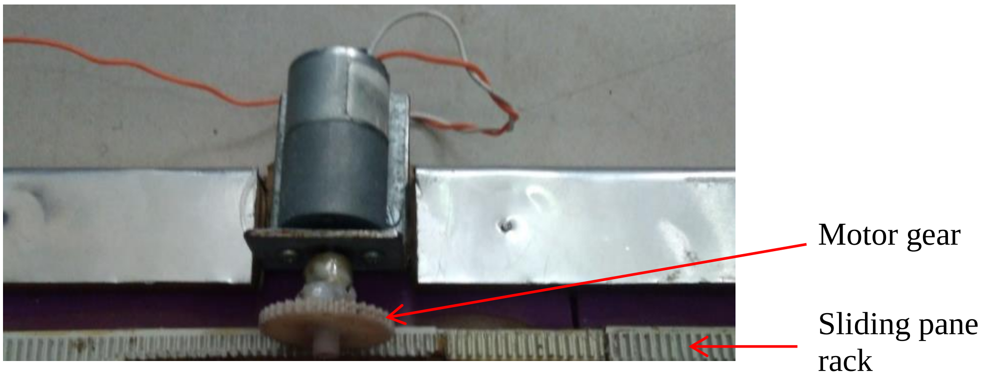

Figure 4.19: Electric motor on sliding window

The automatic window control circuit was built as shown in Figure 4.20 and fitted into the digester as shown in Figure.4.21. The cables from the 12 VDC battery, 12VDC electric motor, temperature relay switch and top and bottom limit switches were connected to the circuit board on a wooden board as shown in the Figure.4.20. The sliding window and circuit were fitted to the greenhouse and the temperature set point knob tuned such that the relay switch switches the motor ON at 35 $^{o}$C and OFF below that temperature. The motor speed control was set at 20 revolutions per minutes and the enable knob left in the ON position to begin digester temperature control.

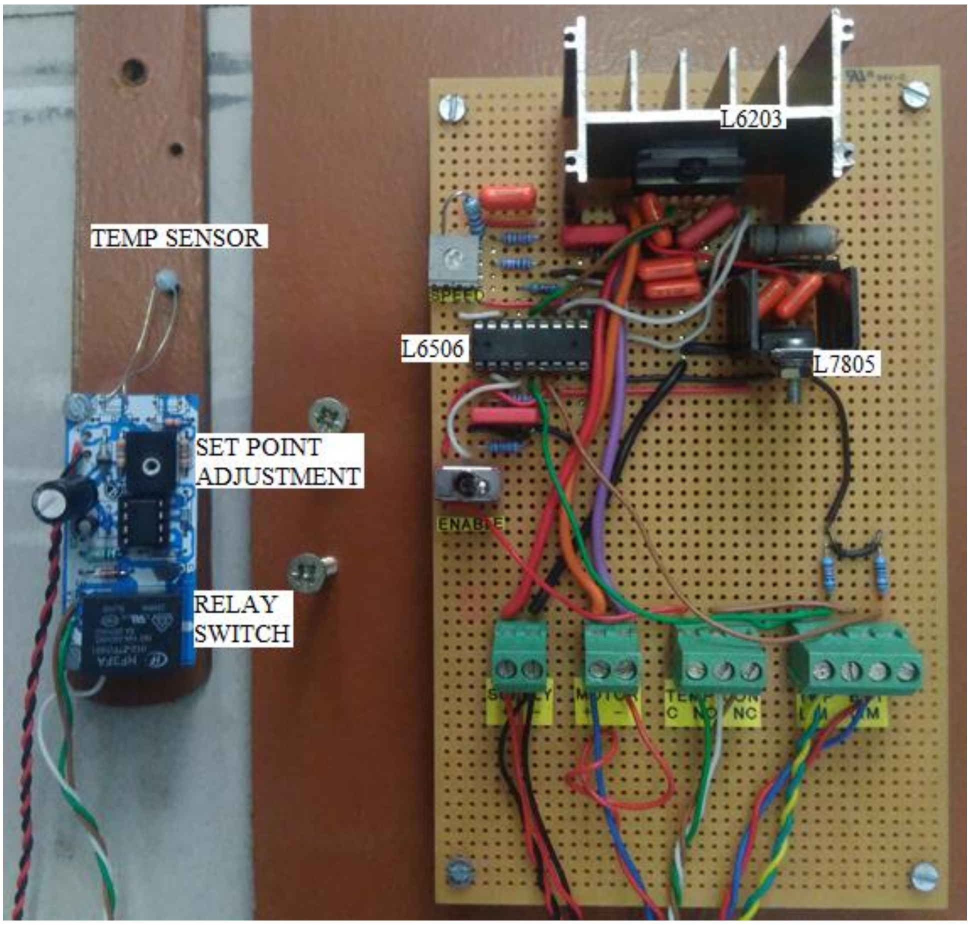

Figure 4.20: Electric circuit of automatic sliding window

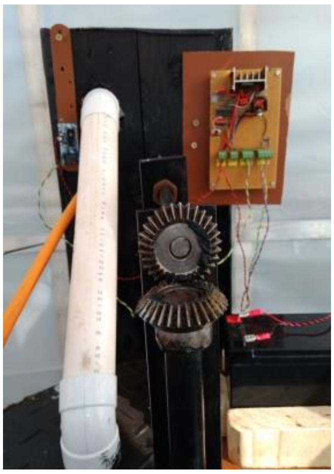

Figure 4.21: Fitted automated sliding window circuit

### 4.4.4 Complete agitated portable biogas digester under greenhouse-regulated temperature

Figure 4.22 shows the constructed agitated portable biogas digester under greenhouse-regulated temperature, placed in a garden for utilization of the digestate (fertilizer) produced after digestion for horticultural purposes. A data acquisition system was placed under a shade next to the constructed digester. This was used for the collection of slurry, greenhouse and ambient air temperatures, biogas production, methane yield and some substrate parameter data as outlined in the following section.

Figure 4.22: Greenhouse regulated temperature biogas digester

## 4.5 SUMMARY

The biogas digester design was based on the specifications of temperature maintenance at an optimum of 35±1°C, manual agitation, portability and simplicity. The system was described by 2D and 3D dimensional views of annotated diagrams. The digester system included a mild steel cylindrical digester vessel with a 10 mm thick flat top flange, 3 mm thick cylindrical section and 3 mm thick tori-spherical bottom. This was the minimum workable thickness enabling the vessel to withstand internal pressure to be exerted by biogas during digestion. The thickness was also thin enough to allow for efficient thermal energy transfer across the vessel wall made of mild which has a good thermal conductivity of 54 W/mK. The digester vessel was painted black to increase its absorptivity of solar and thermal radiation. An anchor impeller with a diameter 95% that of the vessel was designed since it is suitable for the gentle and slow agitation of thick pastes such as most substrate slurries. For temperature control, a portable greenhouse with a double layer of polyethylene plastic cover for solar radiation transmission and thermal radiation insulation was designed and constructed to house the digester vessel. The greenhouse had a wooden base for thermal radiation insulation and an automated ON/OFF temperature-controlled sliding window to control the greenhouse air temperature through ventilation. The greenhouse design was done is such a way as to minimize thermal energy losses through conduction, convection and infiltration. This was achieved by use of a double layer of polyethylene plastic trapping an air film to provide insulation against heat loss by conduction and convection. Thermal energy loss through infiltration was minimized by ensuring airtightness of the greenhouse structure. When the greenhouse temperature crosses the set point of 35°C, the 12VDC ON/OFF temperature-controlled relay switch actuates a 12VDC motor to open the sliding window and vent warm air out of the greenhouse, replacing it with cooler air hence decreasing the greenhouse temperature. Below the set point, the motor is actuated to move in the opposite direction hence closing the window. A hysteresis band of 2°C prevented the continuous rapid switching of the relay above and below the set point. This way the greenhouse temperature was maintained within a narrow range of 32-37°C. The slurry temperature in turn was maintained within a narrower range of 34-36°C, giving the desired optimum of 35°C.

# CHAPTER 5: DIGESTER PERFORMANCE EVALUATION

## 5.1 INTRODUCTION

This chapter presents the performance of the biogas digester designed and constructed in this work. The digester performance was measured on the basis of its ability to maintain slurry temperature within a narrow mesophilic range of 34 – 36$^{o}$C, and a neutral pH of 7 during the digestion period. The COD destruction rate and extent, and biogas quality possible with the new design were determined in comparison with the results from a sawdust-insulated fixed dome digester in the digestion of cow dung from the same source that was used in this research i.e the dairy farm at the University of Fort Hare (Mukumba et.al.).

## 5.2 TEMPERATURE VARIATION

Figure 5.1 shows the ambient temperature, $T_{amb}$, greenhouse air temperature, $T_a$, and slurry temperature, $T_s$ variation with time for the month of July, 2017. This is the coldest month in climate of the Eastern Cape Province.

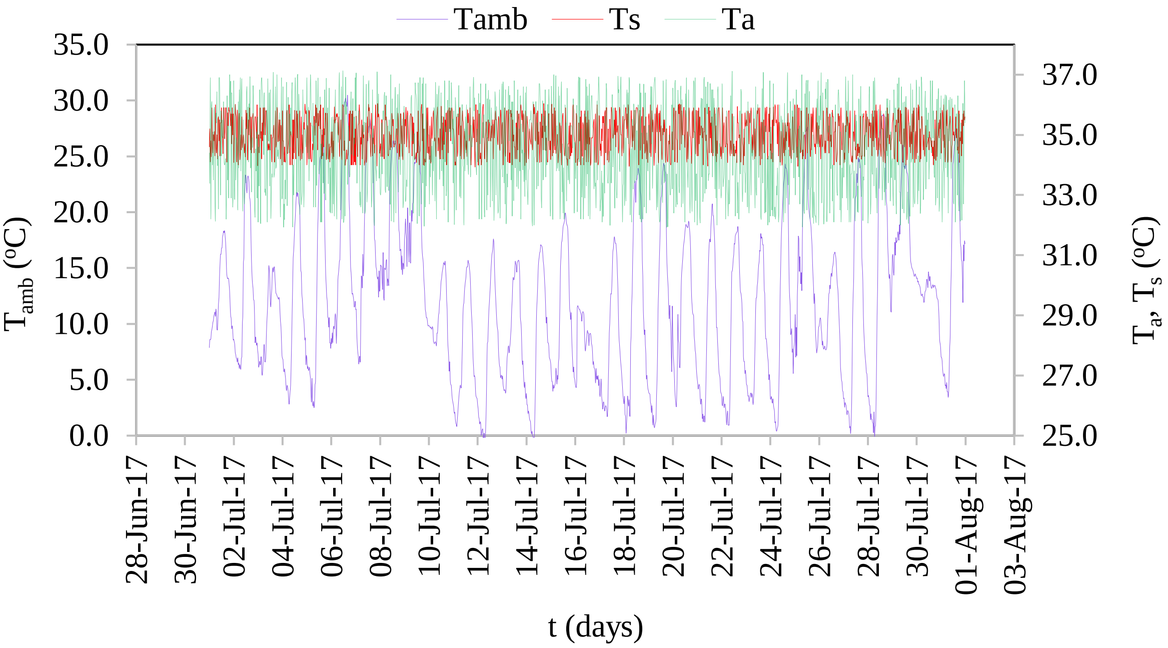

Figure 5.1: Ambient, Greenhouse and Slurry temperature variation for a month

The inequalities [5.1] – [5.3] show the ambient, greenhouse and slurry temperature variations during the month:

$$-0.8^{o}C \leq T_{amb} \geq 30.2^{o}C \qquad [5.1]$$

$$32^{o}C \leq T_{a} \leq 37^{o}C \qquad [5.2]$$

$$34^{o}C \leq T_{s} \leq 36^{o}C \qquad [5.3]$$

During this period, it is shown from the figure that; $T_{a} > T_{amb}$ and $T_{s} > T_{amb}$.

Figure 5.2 shows the temperature variations with time measured at 30-minute intervals over a period of two typical days in July. The days were chosen, because they are generally a true representation of the ambient temperature pattern for the whole month at the University of Fort Hare.

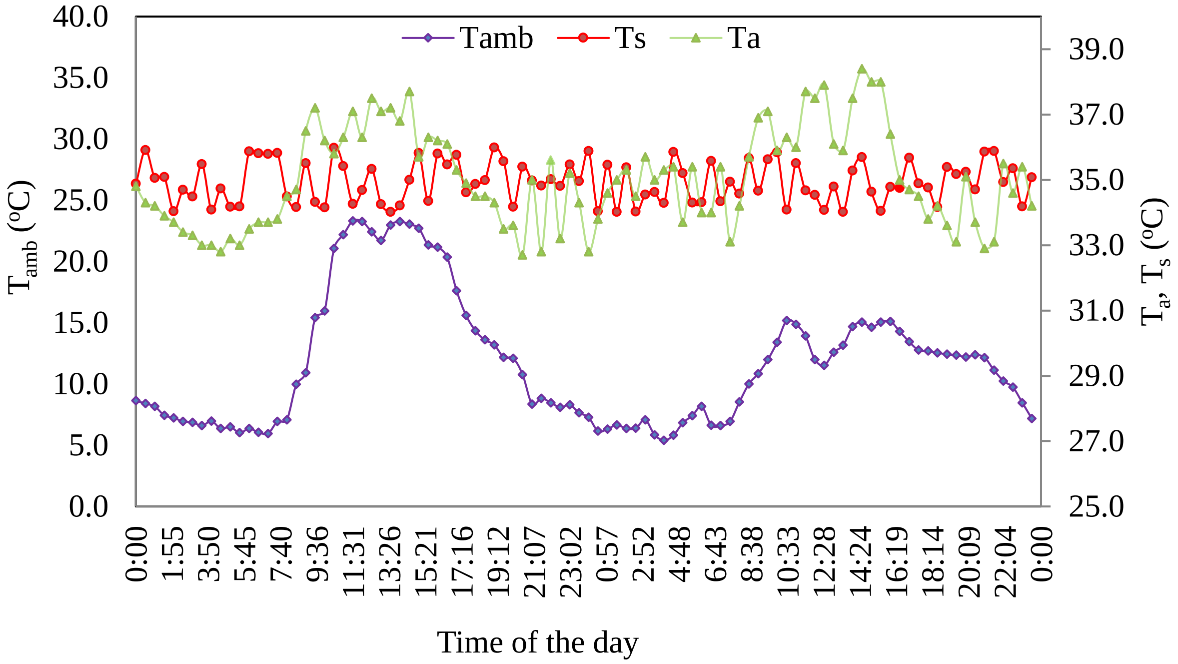

Figure 5.2: Ambient, Greenhouse and Slurry temperature variation for 2 days

During the 2 days;

$$5.4^{o}C \leq T_{amb} \geq 23.3^{o}C \qquad [5.6]$$

$T_{a} > T_{amb}$ at any given time due to the greenhouse effect and the insulation against heat loss.

$T_s > T_{amb}$ always because of the greenhouse effect and also bacterial activity facilitating exothermic reactions within the digestion chamber as stated by Jarvis Anna Schnürer and Åsa, (2010).

As shown in Figure 5.2, the temperature variation behaved differently for different times of the day. Between 0.00Hours and 08.00Hours, $T_s > T_a$ due to the absence of solar radiation in the night. The slurry has a higher heat capacity than the air within the greenhouse therefore it was able to retain heat better than the air. During this period, $T_a$ decreased from 34.8°C to a minimum of 32.1°C at 06.30Hours due to thermal energy losses through infiltration and the fact that there wasn't 100% insulation efficiency.

After 06.30Hours, $T_a$ increased gradually and at 08.30Hours, $T_a = T_s = 34.7^oC$. At sunrise $T_a > T_s$ due to the greenhouse effect after the rising of the sun. Between 08.30Hours and 18.00Hours (sunset), $T_a > T_s$ and fluctuated under controlled ventilation. The slurry temperature also fluctuated within its range of 34 – 36°C due to the influence of the greenhouse temperature and dynamic bacterial activity.

At 18.00Hours, $T_a = T_s = 34.5^oC$ and from then it continued to gradually decrease below the slurry temperature into the night till it reached a minimum of 31.9°C at 05.30Hours and started rising again with the rising of the sun.

A linear regression of the $T_s$, $T_a$ and $T_{amb}$ data in Kelvins gave the equation:

$$\ln T_s = 1.043 \ln T_a + 0.064 \ln T_{amb} + 0.8313 \qquad [5.7]$$

Hence:

$$T_s = 0.8313 T_a^{1.043} T_{amb}^{0.064} \qquad [5.8]$$

This implies that $T_a$, with a higher power of 1.043, affected the slurry temperature more than the $T_{amb}$. This was due to the high conductivity of the mild steel vessel wall separating the slurry from the greenhouse air as opposed to the insulating greenhouse wall separating the greenhouse air from the ambient conditions. The positive relationship however was due to the greenhouse effect. Incorporating the initial slurry temperature, $T_{0s}$ in the linear regression gave equations [5.9] and [5.10]:

$$\ln T_s = 1.27077 \ln T_{0s} + 0.087894 \ln T_a + 0.003643 \ln T_{amb} + 0.7612 \qquad [5.9]$$

$$T_s = 0.7612 T_{0s}^{1.27077} T_a^{0.087894} T_{amb}^{0.003643} \qquad [5.10]$$

The initial slurry temperature had a higher and more significant impact to the slurry temperature measured at any given point than the greenhouse and ambient temperatures since it has a higher power of 1.27077 as shown in equation [5.10]. This was due to the fact that the slurry had a high heat capacity and would require more thermal energy before significantly responding to any temperature changes around it.

## 5.3 BIOGAS YIELD

For digester performance evaluation in terms of gas production, the gas yield from dairy cow dung was used. The characterization parameters for the cow dung used were total solids content of 162348.67 mg/ℓ, total alkalinity within the range of 1988 – 2347 mg/ℓ and other parameters as summarized in table 5.1. The total alkalinity was sufficient for the maintenance of optimal bacterial activity and digestion system stability (Okudoh, Trois, Workneh, & Schmidt, 2014; Town & September, 1994). With an ammonia-nitrogen range as low as 128 – 235 mg/ℓ, the potential for process inhibition was minimal.

Table 5.1: Characterisation parameters for dairy cattle dung

| **Parameter** | **Value** |
|---|---|
| Total solids (mg/ℓ) | 162348.67 |
| COD (mg/ℓ) | 37 879 |
| Volatile solids (mg/ℓ) | 116543.98 |
| Volatile solids / Total solids % | 71.79 |
| Total alkalinity (mg/ℓ) | 1988 - 2347 |
| Ammonium-nitrogen (mg/ℓ) | 128 - 235 |
| Calorific value (MJ/g) | 25.29 |

Anaerobic digestion of the dairy cattle dung was carried out at a temperature range of 35 ± 1$^{o}$C for a retention time of 31 days. Figure 5.3 shows the biogas yield attained during this period.

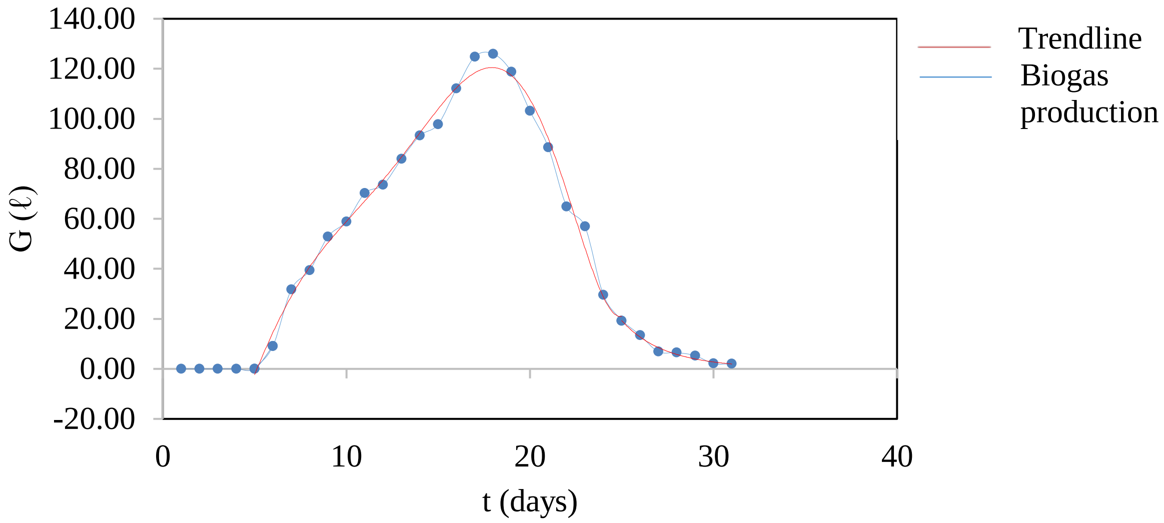

Figure 5.3: Biogas yield for dairy cattle dung

Figure 5.3 shows that biogas production started on day 6 where 9.13 litres were measured. This was so because no inoculum was added to start-up of the anaerobic digestion process which according to literature might have started gas production as early as day 2 (Cheng et al., 2014; Spuhler, 2014). The gas production, $G$, over time, $t$, increased gradually according to the function of the line and curves of best fit in Figure 5.3:

$$G = \begin{cases} 0 & if \quad t \le 5 \\ 9\times10^{-5}t^{6} - 0.0073t^{5} + 0.2139t^{4} - 3.0105t^{3} + 20.639t^{2} & if \quad 5 < t \le 27 \\ -48.649t - 11.06 & \\ 262627 e^{-.0382\,t} & if \quad t > 27 \end{cases} \qquad [5.11]$$

The gas production function shows that the daily rate of gas production fluctuated between Day 6 and Day 27 although the general trend was an increase in gas production reaching a maximum value of 125.98 litres on day 18, followed by a decrease down to 6.85 litres on day 27. These fluctuations were due to the continuously dynamic activity of the anaerobic micro-organisms in response to slight temperature and pH changes and agitation as fresher substrate was exposed for digestion. Thereafter, an exponential decrease to smaller quantities of gas took place up to day 31 with 2.02 litres. This was a result of the depletion of fresh substrate regardless of agitation and change in temperature, pH, or any other physico-chemical properties.

Figure 5.4 shows the cumulative biogas yield.

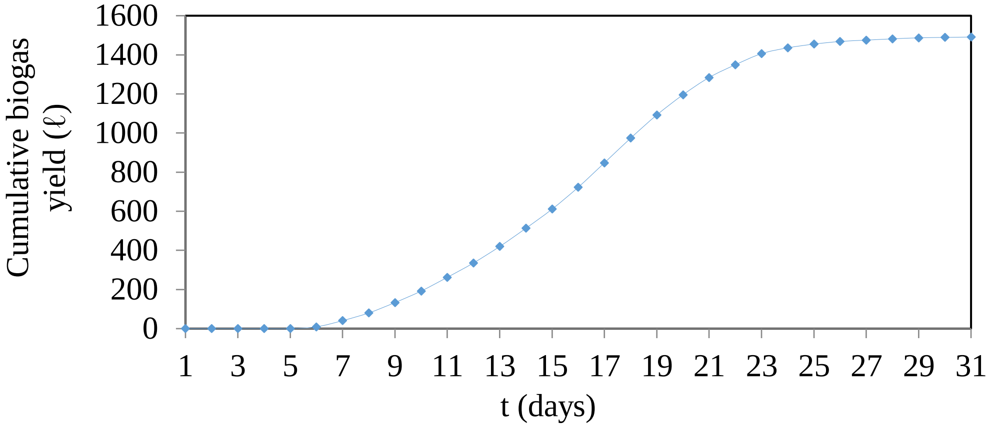

Figure 5.4: Cumulative biogas production from dairy cattle dung

From Figure 5.4, it can be observed that the total biogas produced over the 31 days of anaerobic digestion of dairy cattle dung was 1491.10ℓ, 65.3% (973.78ℓ) of which was produced between Days 6 and Day18. During this period the slurry will be rich in the biodegradable organic fraction of the substrate. A cumulative biogas production function, $G(t)$ determined from the curve of best fit in Figure 5.4 is given in equation [5.12]:

$$G(t) = 0.0011x^5 - 0.0878x^4 + 2.2418x^3 - 18.619x^2 + 61.919x - 61.178 \qquad [5.12]$$

The average daily biogas production $\langle G \rangle$ was determined from equation [5.13]:

$$\langle G \rangle = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} G(t)dt \approx 48\,\ell \qquad [5.13]$$

Figure 5.5 shows the variation of the production of $CH_4$ and $CO_2$.

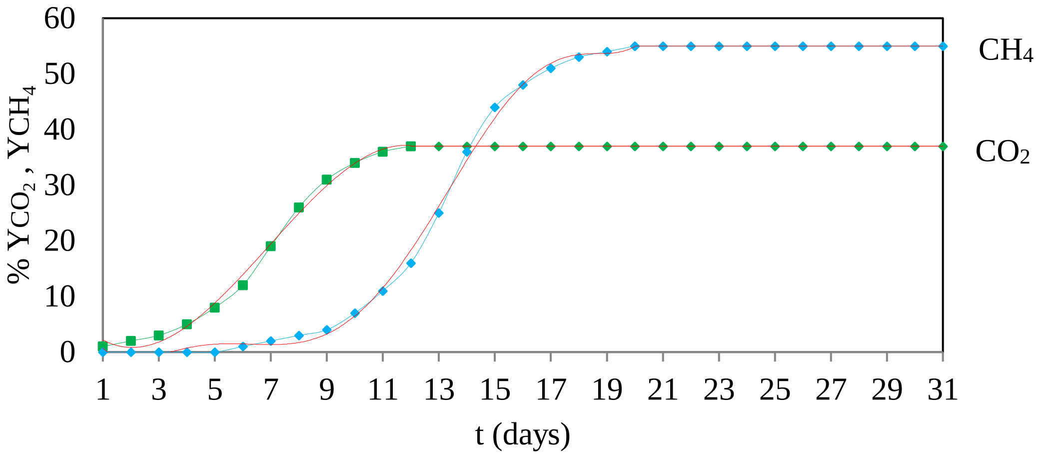

Figure 5.5: Variation of the production of $CH_4$ and $CO_2$

With reference to Figure 5.5, the $CO_2$ content was 0.04% (composition in air) on Day 1 and it increased starting on Day 2 before attaining to a constant value on Day 11 and onwards. The $CO_2$ production pattern followed equation [5.14].

$$Y_{CO_2} = \begin{cases} 0.04 & if \quad t < 2 \\ -0.0785t^3 + 1.6287t^2 - 5.6774t + 6.303 & if \quad 2 \le t \le 11 \\ 37 & if \quad t > 11 \end{cases} \qquad [5.14]$$

The production of $CO_2$ is due to 1. The presence of some aerobic bacteria in the digester before the evacuation of air from the digester by biogas formation which facilitated the reaction of $O_2$ with carbohydrates to produce $CO_2$ and 2. The action of acidogenic bacteria in forming fatty acids from the organic feed, which were then decomposed by acetotrophic methanogens to $CH_4$ and $CO_2$ according to equation [2.2]:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

The decrease in $CO_2$ was a result of $O_2$ depletion in the digester vessel and conversion of some of the $CO_2$ to $CH_4$ by the action of Hydrogenotrophic methanogens according to equation [2.1]:

$$CO_2 + 4H_2 \rightarrow CH_4 + CO_2$$

The $CO_2$ however reached a constant composition after Day 11 due to the equilibrium reached between its formation and usage as shown in equations [2.1] and [2.2].

The $CO_2$ production pattern followed equation [5.15].

$$Y_{CH_4} = \begin{cases} 0 & if \quad t < 7 \\ 8\times10^{-5}t^6 - 0.0048t^5 + 0.1082t^4 - 1.0937t^3 + 5.2081t^2 & if \quad 7 \le t \le 20 \\ -10.729t + 6.9506t & \\ 55 & if \quad t > 20 \end{cases} \qquad [5.15]$$

$CH_4$ production began on Day 6 and increased gradually to attain a constant percentage of 55% on day 20 onwards. No $CH_4$ was produced before Day 6 because the methanogenic bacteria waited till the formation of fatty acids on which they feed in order to produce methane (Ghosh & Bhattacherjee, 2013; Mshandete & Parawira, 2009). On Day 14 the $CH_4$ content rose above the $CO_2$ content since none of the two methanogenic processes uses $CH_4$ as a reactant unlike in the case of $CO_2$. The $CH_4$ content however reached a maximum constant value due to the continual production of $CO_2$ by the same methanogenic processes which leads to an equilibrium point.

The methane yield achieved is higher than the 50% that Mukumba et al found in their digestion of cow dung using a fixed dome batch biogas digester insulated with sawdust (Mukumba & Makaka, 2014; Mukumba et al., 2015). This difference can be attributed to the fact that in the current work the slurry temperature was maintained at 35°C while Mukumba et al used 30°C.

Table 5.2 shows the final % composition of $CH_4$, $CO_2$, $H_2S$ and other gases

Table 5.2: Biogas composition after digestion

| **Gas** | **Composition (%)** |
|---|---|
| Methane ($CH_4$) | 55 |
| Carbon dioxide ($CO_2$) | 37 |
| Hydrogen sulphide ($H_2S$) | 0 |
| Other gases | 8 |

## 5.4 pH VARIATION

Figure 5.6 shows the relationship between the biogas yield and the pH values measured during the anaerobic digestion process.

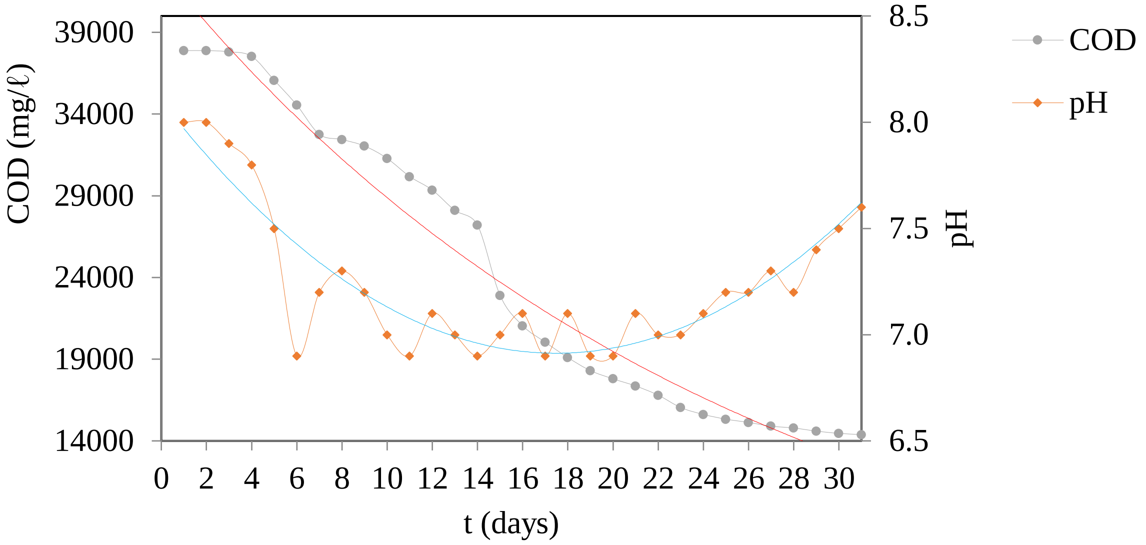

Figure 5.6: Relationship between COD and pH ranges for dairy cattle dung digestion

Due to the presence of the highly digestible organic fraction of the cow dung and the increased rate of COD destruction to form volatile fatty acids (acidogenesis) between days 4 and 6, the pH dropped from 8.0 on day 2 to 6.9 on day 6 and begins to fluctuate between 6.9 and 7.3, giving an average pH of 7.2. This fluctuation was a result of the balance between COD destruction by acid-forming (acidogens) and acid-depleting bacteria (methanogens) since the acidogenesis and methanogenesis processes occur simultaneously (Lemmer, Naegele, & Sondermann, 2013). This narrow pH range indicated a good buffering capacity of the cow dung used as a result of its suitable alkalinity (1988 – 2347) (Anozie, Layokun, & Okeke, 2017). From day 19 the pH began to increase as the fatty acids got depleted. The pH variation with time can be represented by the quadratic function:

$$pH = 0.0039t^2 - 0.136t + 8.1018 \qquad [5.16]$$

With reference to equation, the pH decreases then increases within a very narrow range which suggests good buffering capacity and efficient anaerobic digestion. An exponential decrease in COD takes place according to equation [5.17]:

$$COD = 42817e^{-0.039t} \qquad [5.17]$$

This shows that COD destruction was fast and efficient during the digestion period having a half-life, $t_{\frac{1}{2}}$ of 17 days.

$$t_{\frac{1}{2}} = \frac{\ln\frac{1}{2}}{-0.039} = 17\,days \qquad [5.18]$$

Figure 5.7 shows the relationship between biogas yield and pH. It is clearly shown that the pH drops during the first 6 days i.e. before methanation which depletes the formed fatty acids. The highest biogas yield is obtained at an optimum pH of 7.2 between Day 9 and Day 24 when the pH is somewhat constant as shown in Figure 5.7. After day 19, towards the end of the digestion process, the pH begins to rise again as gas production decreases due to depletion of fatty acids.

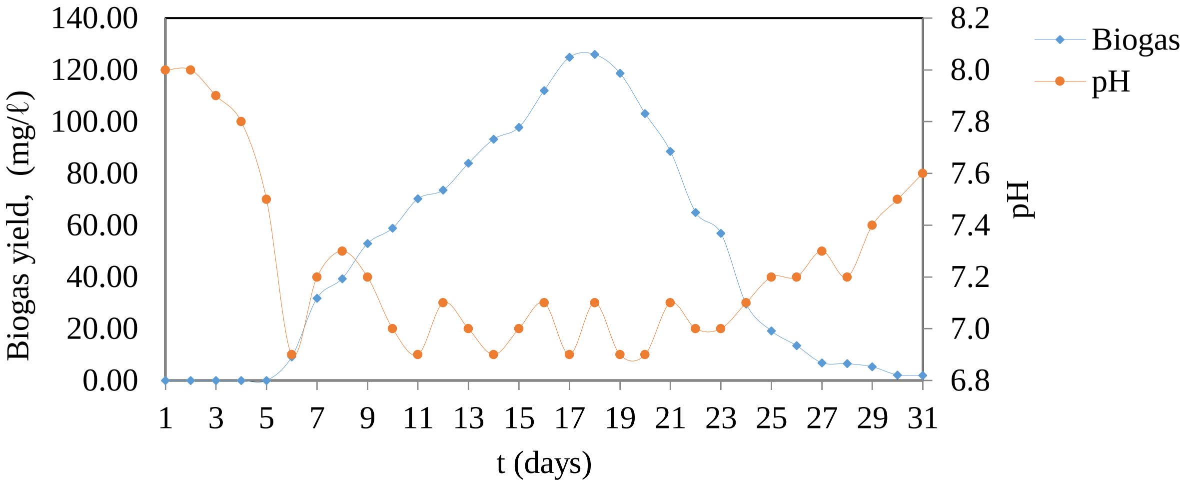

Figure 5.7: Relationship between biogas yield and pH range for dairy cattle

## 5.5 COD DESTRUCTION

Figure 5.8 shows the COD destruction rate in relation to biogas yield. Upon entry into the digester, the cow dung had a COD of 37 879 mg/ℓ which dropped to a final value of 14388 mg/ℓ in the effluent.

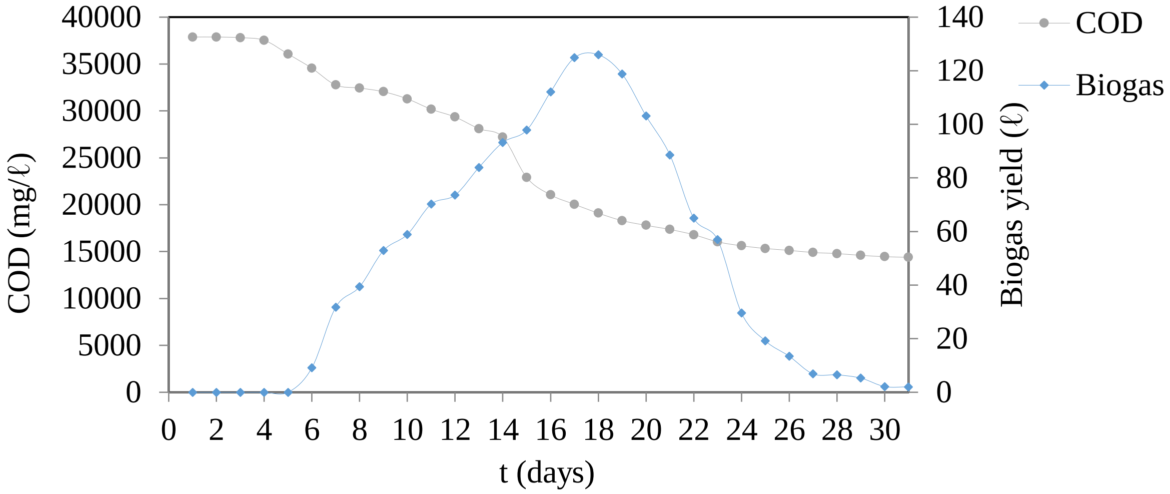

Figure 5.8: Relationship between gas yield and COD range for dairy cattle dung

This means that the digester was able to achieve 62 % COD destruction. This agrees with the findings that the maximum COD destruction under mesophilic conditions lies within the range of 60 – 85 % (Kardos, 2011). There was a sharp decrease in COD between days 4 - 7 and 14 - 19 which explains the rapid increase in biogas production on day 6 and 7 and also the maximum biogas production on day 18.

## 5.6 SUMMARY

The ambient, greenhouse and slurry temperatures fluctuated within the ranges $-0.8^{o}C \leq T_{amb} \geq 30.2^{o}C$, $32^{o}C \leq T_{a} \leq 37^{o}C$ and $34^{o}C \leq T_{s} \leq 36^{o}C$ respectively. This indicated that the main objective to maintain the slurry temperature at an optimum mesophilic temperature of 35°C which is very favourable for anaerobic digestion was achieved. $T_a > T_{amb}$ at any given time due to the greenhouse effect and the insulation against heat loss and $T_s > T_{amb}$ because of the greenhouse effect and the exothermic bacterial activity within the digester. During night hours, $T_s > T_a$ due to the absence of solar radiation and the greenhouse effect and also the fact that the slurry has a higher heat capacity than the greenhouse air thus it was able to retain heat better than the air. Decreases in $T_a$ were due to thermal energy losses through infiltration and insufficient insulation i.e. conductive and convective losses. During the day $T_a > T_s$ due to the greenhouse effect after the rising of the sun. $T_a$ and $T_s$ also fluctuated within their narrow ranges as stated above due to controlled ventilation. The equation:

$T_s = 0.8313 T_a^{1.043} T_{amb}^{0.064}$, related the three temperatures affecting the digester system. $T_a$ affected the slurry temperature more than the $T_{amb}$ due to the high conductivity of the mild steel vessel wall separating the slurry from the greenhouse air compared to the insulating greenhouse wall separating the greenhouse air from the ambient conditions. The relationship: $T_s = 0.7612 T_{0s}^{1.27077} T_a^{0.087894} T_{amb}^{0.003643}$ showed that the initial slurry temperature had a higher and more significant impact to the slurry temperature measured at any given point than the greenhouse and ambient temperatures since the slurry has a high heat capacity and requires more thermal energy so as to significantly respond to temperature changes.

The general biogas production trend was an increase in gas production reaching a maximum value of 125.98 litres on Day 18, followed by a decrease down to 6.85 litres on day 27. The fluctuations were due to the continuously dynamic activity of the anaerobic micro-organisms in response to slight temperature and pH changes and agitation. An exponential decrease took place from Day 27 to Day 31 with 2.02 litres as a result of the depletion of fresh substrate. The average daily biogas production $\langle G \rangle$ was about $48\ell$.

The biogas produced comprised $CO_2$ and $CH_4$. $CO_2$ was formed earlier, before $CH_4$ due to the action of aerobic bacteria on carbohydrates to produce $CO_2$ and later and the decomposition of fatty acids produced by acidogenic bacteria to $CH_4$ and $CO_2$. The final $CH_4$ content was 55% which is better than the 50% achieved by a saw dust-insulated fixed dome digester after digestion dairy cattle dung from the same source as that used in this work (Mukumba et.al.).

The pH fluctuated within a range of 6.9-7.3, giving an optimum of 7.2, which suggests good buffering capacity and efficient anaerobic digestion. An exponential decrease in COD with a half-life of about 17 days was achieved and the percentage COD destruction was 62%. The favourable temperature, pH, and slurry agitation conditions and efficient COD destruction led to a higher methane yield of 55% from cow dung.

# CHAPTER 6: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 6.1 INTRODUCTION

This chapter gives a summary of the findings of the literature review done on the types of digesters in current use, the possibility of using the greenhouse effect to control the operation temperature of a biogas digester and the design, construction and performance evaluation of a greenhouse temperature-regulated, agitated biogas digester. From the findings, some conclusions will be drawn and finally some recommendations will be made.

## 6.2 SUMMARY OF FINDINGS

Biogas is produced in the process of anaerobic digestion. Major factors affecting biogas production are temperature, pH, and agitation. Small scale digester designs in current use include the In-situ cast concrete, Brick and motor fixed dome, Bio-bag, Plastic roto-mould and Floating dome digesters. Most small-scale digesters have poor temperature control and inefficient agitation and hence can only produce small biogas quantities and methane yields. The use of a greenhouse for small digester operation temperature control is an attractive solution to the problem of poor temperature control and inefficient agitation. In a greenhouse structure housing a digester, solar radiation is transmitted through the greenhouse cover and a fraction of the transmitted radiation is absorbed by the digester and conducted into the substrate slurry as thermal energy hence raising the slurry temperature. The other fraction is radiated back into the greenhouse space as thermal radiation. This thermal radiation has a longer wavelength and lower frequency than the solar radiation and hence cannot be transmitted back into the atmosphere through the greenhouse cover. Thermal energy therefore accumulates within the greenhouse resulting in the heating of the slurry. Some thermal energy is however lost from the greenhouse to the atmosphere through conduction across the cover, convection from the air to the cover and away, ventilation and infiltration through openings in the greenhouse walls. A digester vessel is a low-pressure vessel since it operates under a differential pressure, $\Delta P > 0.5\, bars$ and has a diameter $\phi > 150mm$. The internal pressure to be exerted to the vessel is considered in the determination of the vessel dimensions and wall thickness.

The biogas digester design was based on the specifications of temperature maintenance at an optimum of 35±1$^{o}$C, manual agitation, portability and simplicity.

The ambient, greenhouse and slurry temperatures fluctuated within the ranges $-0.8^{o}C \leq T_{amb} \geq 30.2^{o}C$, $32^{o}C \leq T_a \leq 37^{o}C$ and $34^{o}C \leq T_s \leq 36^{o}C$ respectively and this shows that the main objective to maintain the slurry temperature at an optimum of 35$^{o}$C was achieved. $T_a > T_{amb}$ at any given time due to the greenhouse effect and the insulation against heat loss and $T_s > T_{amb}$ because of the greenhouse effect and the exothermic bacterial activity within the digester. During night hours, $T_s > T_a$ due to the absence of solar radiation and the greenhouse effect and also the fact that the slurry has a higher heat capacity than the greenhouse air thus it was able to retain heat better than the air. A decrease in $T_a$ was due to thermal energy losses through infiltration and insufficient insulation i.e. conductive and convective losses. During the day $T_a > T_s$ due to the greenhouse effect after the rising of the sun. $T_a$ and $T_s$ also fluctuated within their narrow ranges as stated above due to controlled ventilation. The equation: $T_s = 0.8313 T_a^{1.043} T_{amb}^{0.064}$, related the three temperatures affecting the digester system. $T_a$ affected the slurry temperature more than the $T_{amb}$ due to the high conductivity of the mild steel vessel wall separating the slurry from the greenhouse air compared to the insulating greenhouse wall separating the greenhouse air from the ambient conditions. The relationship: $T_s = 0.7612 T_{0s}^{1.27077} T_a^{0.087894} T_{amb}^{0.003643}$ showed that the initial slurry temperature had a higher and more significant impact to the slurry temperature measured at any given point than the greenhouse and ambient temperatures since the slurry has a high heat capacity and requires more thermal energy so as to significantly respond to temperature changes.

The general biogas production trend was an increase in gas production reaching a maximum value of 125.98 litres on Day 18, followed by a decrease down to 6.85 litres on day 27. The fluctuations were due to the continuously dynamic activity of the anaerobic micro-organisms in response to slight temperature and pH changes and agitation. An exponential decrease took place from Day 27 to Day 31 with 2.02 litres as a result of the depletion of fresh substrate. The average daily biogas production $\langle G \rangle$ was about 48ℓ.

$CO_2$ and $CH_4$ were the two biogas constituents observed. $CO_2$ was formed earlier, before $CH_4$ due to the action of aerobic bacteria on carbohydrates to produce $CO_2$ and later and the decomposition of fatty acids produced by acidogenic bacteria to $CH_4$ and $CO_2$. The final $CH_4$ content was 55% which is better than the 50% achieved by a saw dust-insulated fixed dome digester after digestion dairy cattle dung from the same source as that used in this work (Mukumba et.al.). The $CO_2$ content was 37% and the rest was water vapour and other gases. The pH fluctuated within a range of 6.9-7.3, giving an optimum of 7.2, which suggests good buffering capacity and efficient anaerobic digestion. An exponential decrease in COD with a half-life of about 17 days was achieved and the percentage COD destruction was 62%.

## 6.3 CONCLUSIONS

The use of a greenhouse temperature regulated, agitated portable biogas digester for anaerobic digestion of wastes for the production of biogas improves the digestion efficiency and increases methane yield. The common challenges of poor temperature control and inefficient agitation which lead to poor biogas production are greatly reduced by this digester design. Giving a methane yield from dairy cattle dung of 55%, which is comparable to the 50% found in literature, achieved by other digester designs such as the fixed dome with saw dust insulation, the current design becomes a more attractive option since it is portable and can be installed for use in any given location (rural, urban, multi-storey and rocky terrains), and can operate at a higher optimum temperature of 35$^o$C due to the heating effected by the greenhouse as opposed to 30$^o$C or lower temperatures. The use of readily available and cheap construction materials also adds to the attractiveness of the design.

## 6.4 RECOMMENDATIONS

The digester performance evaluation in this work was done using dairy cattle dung from the University of Fort Hare dairy farm. It is recommended that other substrate types such as domestic wastes, especially kitchen waste, vegetable wastes, pig manure, donkey manure, etc., be digested using this digester design for further design performance evaluation. Semi-continuous digester feeding should also be done for further digester performance evaluation since in this work only the batch digestion mode was used for experimental purposes. A mathematical model of this digester design can be developed and used in the determination of optimum biogas production parameters using the design under various feeding and operating conditions.

# REFERENCES

Angelidaki, I., Mogensen, A. S., & Ahring, B. K. (2000). Degradation of organic contaminants found in organic waste. Biodegradation, 11(6), 377–383.

Anozie, A. N., Layokun, S. K., & Okeke, C. U. (2017). An Evaluation of a Batch Pilot-Scale Digester for Gas Production from Agricultural Wastes. An Evaluation of a Batch Pilot-Scale Digester for, 8312(September).

Aqualytic®. (2015). Principles of Photometry, Aqualytic user manual.

Aqualytic®. (n.d.). General Catalogue.

Aquarius Technologies. (2011). On/Off control.

Banos, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., Alcayde, A., (2011). Optimization methods applied to renewable and sustainable energy: A review. Renewable and Sustainable Energy Reviews, 15(4), 1753–1766.

Benefits, B. (n.d.). The EZ- Digester Organic waste, Digestate & Appliances, 2.

Benefits, B., Department of Energy, Gracia Munganga, Hildebrandt, P. D., Mamphweli, S., Town, C. Bucking, C. (2014). Biogas Technology: Current Trends, Opportunities and Challenges. Water Intake and Hydratation Physiology during Childhood, 30 March, 166.

Bond, T., & Templeton, M. R. (2011). History and future of domestic biogas plants in the developing world. Energy for Sustainable Development, 15(4), 347–354.

Bruun, S., Jensen, L. S., Khanh Vu, V. T., & Sommer, S. (2014). Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb? Renewable and Sustainable Energy Reviews, 33, 736–741.

Buschermohle, M. J., & Grandle, G. F. (2012). W017-Controlling the Environment in Greenhouses Used for Tomato Production. The University of Tennessee Agricultural Extension Service.

Cheng, S., Li, Z., Mang, H. P., & Huba, E. M. (2013). A review of prefabricated biogas digesters in China. Renewable and Sustainable Energy Reviews, 28, 738–748.

Cheng, S., Li, Z., Mang, H. P., Huba, E. M., Gao, R., & Wang, X. (2014). Development and application of prefabricated biogas digesters in developing countries. Renewable and Sustainable Energy Reviews, 34, 387–400.

Christoforou, E. A., Fokaides, P. A., & Kyriakides, I. (2014). Monte Carlo parametric modelling for predicting biomass calorific value. Journal of Thermal Analysis and Calorimetry, 1789–1796.

Colorado State University. (1978). Solar radiation. Solar Energy Applications Laboratory. Colorado.

Conradie, D., Researcher, S., Published, C., Building, G., & Essential, T. (2010). Maximising the sun to Solar position, 3, 1–11.

Costa, J. C., Oliveira, J. V., & Alves, M. M. (2016). Response surface design to study the influence of inoculum, particle size and inoculum to substrate ratio on the methane production from Ulex sp. Renewable Energy, 96, 1071–1077.

Coulson and Richardson. (2003). Chemical engineering Design, 6.

Darwin, Cheng, J. J., Liu, Z. M., Gontupil, J., & Kwon, O. S. (2014). Anaerobic Co-Digestion of rice straw and digested swine manure with different total solid concentration for methane production. International Journal of Agricultural and Biological Engineering, 7(6), 79–90.

DEA. (2016). Facilitation of large-scale uptake of alternative transport fuels in South Africa - The case for Biogas, 31.

Deepanraj, B., Sivasubramanian, V., & Jayaraj, S. (2015). Experimental and kinetic study on anaerobic digestion of food waste: The effect of total solids and pH. Journal of Renewable and Sustainable Energy, 7(6), 63104.

Defacio, P., Pickerel, L., & Rhyne, S. M. (2010). Greenhouse Operation and Management, 34(1).

Department of Energy, Hildebrandt, P. D., Mamphweli, S., Town, C., Wood, C. M., & Bucking, C. (2014). Little green monster biogas digester technical and information manual. Water Intake and Hydratation Physiology during Childhood, 30(March), 87–129.

Development, I., & Auditorium, C. (2015). Biogas Conference 2015 Navigating the Path to Biogas Implementation, (March).

Divya, D., Gopinath, L. R., & Merlin Christy, P. (2015). A review on current aspects and diverse prospects for enhancing biogas production in sustainable means. Renewable and Sustainable Energy Reviews, 42, 690–699.

Divya, D., Gopinath, L. R., & Merlin, C. P. (2014). A Review on Trends issues and Prospects for Biogas Production in Developing Countries. International Research Journal of Environment Sciences, 3(1), 62–69.

Energy, S. (n.d.). Guide to Passive Solar Home Design.

Fulford, D. (1988). Running a biogas programme: a handbook. Intermediate Technology Publications.

Ghosh, R., & Bhattacherjee, S. (2013). A review study on anaerobic digesters with an Insight to biogas production, 2(3), 8–17.

Green, E. F. (1900). Thermal Expansion Properties of Materials. Online, 10(c), 225–232. Retrieved from http://hdl.handle.net/2060/19690000055

GTZ project information and advisory service on appropriate technology (ISAT). (2007). Biogas - Aplication and production development. Biogas Digesters, II, 81.

Guo, H., Du, L., Liang, J., Yang, Z., Cui, G., & Zhang, K. (2017). Influence of Alkaline-Thermal Pretreatment on High- Solids Anaerobic Digestion of Dewatered Activated, 12(1), 195–210.

Guo, M., Song, W., & Buhain, J. (2015). Bioenergy and biofuels: History, status, and perspective. Renewable and Sustainable Energy Reviews, 42, 712–725.

Hamilton, D. W. (2014). Anaerobic Digestion of Animal Manures : Types of Digesters. Oklahoma Cooperative Extension Service, BAE-1750, 1–4.

Hampton, A. (2010). Thermal Mass and Insulation for Temperate Climates. Environmental Design Guide 65 AH, (November), 1–11.

Hinsley, L. (2015). HDPE vs LLDPE vs LDPE. Global Plastic Sheeting. Retrieved from http://www.globalplasticsheeting.com/hdpe-vs-lldpe-vs-ldpe

Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. Bioresource Technology, 100(22), 5478–5484.

Jarvis Anna Schnürer and Åsa. (2010). Microbiological Handbook for Biogas Plants.

Jim dunlop solar. (2012). Solar Radiation.

Kabir, H., Yegbemey, R. N., & Bauer, S. (2013). Factors determinant of biogas adoption in Bangladesh. Renewable and Sustainable Energy Reviews, 28, 881–889.

Kalogirou, S. (2014). Chapter 6 - Solar Space Heating and Cooling. Solar Energy Engineering (Second Edition).

Kangle, K. M., Kore, S. V, Kore, V. S., & Kulkarni, G. S. (2012). Recent Trends in Anaerobic Codigestion : A Review. Universal Journal of Environmental Research and Technology, 2(4), 210–219.

Kardos, L. (2011). Comparing of mesophilic and thermophilic anaerobic fermented sewage sludge based on chemical and biochemical tests, 9(3), 293–302.

Karlsson, M. (2014). Controlling the Greenhouse Environment, 1–18.

Kharseh, M. (n.d.). Solar Radiation Calculation.

Klavon, K. H., & Lansing, S. (2010). Small-scale anaerobic digestion in the United States: Design Options and Financial Viability.

Kougias, P. G., Boe, K., & Angelidaki, I. (2013). Effect of organic loading rate and feedstock composition on foaming in manure-based biogas reactors. Bioresource Technology, 144, 1–7.

Kralova, I., & Sjöblom, J. (2010). Biofuels–Renewable Energy Sources: A Review. Journal of Dispersion Science and Technology, 31(3), 409–425.

Lau, A. K., & Staley, L. M. (1989). Solar radiation transmission and capture in greenhouses, (August 1988).

Lemmer, A., Naegele, H. J., & Sondermann, J. (2013). How efficient are agitators in biogas digesters? Determination of the efficiency of submersible motor mixers and incline agitators by measuring nutrient distribution in full-scale agricultural biogas digesters. Energies, 6(12), 6255–6273.

Li, Y., Hua, D., Zhang, J., Gao, M., Zhao, Y., Xu, H., … Zhang, X. (2014). Influence of inoculum to substrate ratios (ISRs) on the performance of anaerobic digestion of algal residues. Annals of Microbiology, 64(3), 955–960.

Lusk, P. (1998). Methane Recovery from Animal Manures The Current Opportunities Casebook. Midwest Research Institute for the U.S. Department of Energy, (September), 150.

Madigan, M. T., Martinko, J. M., Dunlap, P. V, & Clark, D. P. (2008). Brock Biology of microorganisms 12th edn. International Microbiology, 11(February), 65–73.

Mao, C., Feng, Y., Wang, X., & Ren, G. (2015). Review on research achievements of biogas from anaerobic digestion. Renewable and Sustainable Energy Reviews, 45, 540–555.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M. S., Fonoll, X., Peces, M., & Astals, S. (2014). A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews, 36, 412–427.

Moestedt, J., Müller, B., Westerholm, M., & Schnürer, A. (2016). Ammonia threshold for inhibition of anaerobic digestion of thin stillage and the importance of organic loading rate. Microbial Biotechnology, 9(2), 180–194.

Mshandete, A. M., & Parawira, W. (2009). Biogas Technology Research in Selected Sub-Saharan African Countries – A Review. African Journal of Biotechnology, 8(2), 116–125.

Mukumba, P., & Makaka, G. (2015). Biogas Production from a Field Batch Biogas Digester Using Cow Dung As a. International Journal of Engineering Research and Science & Technology.

Mukumba, P., Makaka, G., & Shonhiwa, C. (2015). An assessment of the performance of a biogas digester when insulated with sawdust, 4(2), 24–31.

Munganga. (2013). Overview-of-biogas-market-in-South-Africa. Retrieved from http://www.energy.gov.za/files/biogas/presentations/2013-NBC/2013-Overview-of-biogas-market-in-South-Africa.pdf

Nasir, I. M., Omar, R., & Idris, A. (2013). Anaerobic digestion of cattle manure: influence of inoculum concentration pome inoculum lab-scale bioreactor system and operation, 10(1), 22–26.

Nayono, S. E. (2009). Anaerobic digestion of organic solid waste for energy production.

Nnamdi, M., & Victor, N. (2015). Comparative Evaluation of Fiber-glass Reinforced Plastic and Metal Biogas Digesters, 38–44.

Okudoh, V., Trois, C., Workneh, T., & Schmidt, S. (2014). The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review. Renewable and Sustainable Energy Reviews, 39(November), 1035–1052.

Owner’s manual for the Energyweb DIY Biobag digester. (2014), 1–32.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. Renewable and Sustainable Energy Reviews, 15 (3), 1513–1524.

Penn State University. (2014). Covered Lagoon, 2017. Retrieved from http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas/types-of-anaerobic-digesters/covered-lagoon

Pillars, R. (n.d.). Farm-Based Anaerobic Digesters, 1–2.

Pind, P. F., Angelidaki, I., & Ahring, B. K. (2003). Dynamics of the anaerobic process: Effects of volatile fatty acids. Biotechnology and Bioengineering, 82(7), 791–801.

Prasad, R. D. (2012). Empirical Study on Factors Affecting Biogas Production. ISRN Renewable Energy, 2012, 1–7.

R.S. Khurmi J.K. Gupta. (2005). A textbook of, (I).

Rabiner, L. R., & Gold, B. (1985). Mixing and agitation, 6(0), 1308–1310.

Radmanović, K., Đukić, I., & Pervan, S. (2014). Specific Heat Capacity of Wood. Drvna Industrija, 65(2), 151–157.

Rajendran, K., Aslanzadeh, S., & Taherzadeh, M. J. (2012). Household biogas digesters-A review. Energies (Vol. 5).

Raven, R. P. J. M., & Gregersen, K. H. (2007). Biogas plants in Denmark: successes and setbacks. Renewable and Sustainable Energy Reviews, 11(1), 116–132.

Rowse, L. E. (2011). Design of small scale anaerobic digestors for application in rural developing countries, 125.

Saleh, A. (n.d.). Comparison among Different Models of Biogas Plants, 1–11. Retrieved from https://www.academia.edu/1824916/Comparison among different models of biogas plants

Samer, M. (2012). Biogas Plant Constructions. Biogas, 343–369.

Seadi, T. A., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S., & Janssen, R. (2008). Biogas Handbook. Igarss 2014. https://doi.org/10.1533/9780857097415.1.85

Shenzhen Puxin Science and Technology Company Limited. (n.d.). PUXIN family size biogas system, 1–5.

Siliski, A. (n.d.). Everyday Environmental Stewardship.

Singh, S. P., Vatsa, D. K., & Verma, H. N. (1997). Problems with biogas plants in Himachal Pradesh. Bioresource Technology, 59(1), 69–71.

Smith, J., Balana, B. B., Black, H., von Blottnitz, H., Casson, E., Glenk, K., … Gracia Munganga. (2013). The potential of small-scale biogas digesters to alleviate poverty and improve Long term sustainability of ecosystem services in Sub-Saharan Africa. 1st World Sustain. Forum, 5 (10), 2911–2942.

Solar Gain Through Building. (n.d.). Retrieved from http://personal.cityu.edu.hk/~bsapplec/solar3.htm

Spuhler, D. (2014). Anaerobic Digestion (Small-scale). Sustainable Sanitation and Water Management, (2014), 1–10.

Sterling, M. ., Lacey, R. ., Engler, C. ., & Ricke, S. . (2001). Effects of ammonia nitrogen on H2 and CH4 production during anaerobic digestion of dairy cattle manure. Bioresource Technology, 77(1), 9–18.

Sustainable energy authority Victoria. (2002). Energy smart housing manual : design guidelines and case studies. Melbourne, Vic: Melbourne, Vic. : Sustainable Energy Authority Victoria.

Town, C. (2015). Biogas in south africa 4 – 7, (October).

Town, C., & September, A. S. (1994). ve rs ity of ve rs ity e To w.

UGA. (2014). Greenhouses: Heating, Cooling and Ventilation. University of Georgia Extension. https://doi.org/10.1002/ejoc.201200111

WBA. (2013). Biogas – An important renewable energy source. Retrieved from http://www.worldbioenergy.org/sites/default/files/wfm/Factsheet_Biogas.pdf

Weiland, P. (2010). Biogas production: Current state and perspectives. Applied Microbiology and Biotechnology, 85(4), 849–860.

www.omega.com. (n.d.). Introduction to Temperature Controllers.

Xue, B., Zifu, L., Xuemei, W., Xi, H., Shikun, C., Xiaofeng, B., & Ruiling, G. (2017). Online measurement of alkalinity in anaerobic co-digestion using linear regression method. Int J Agric & Biol Eng, 10(1), 176–183.

Yao, N., Liu, Z., Chen, Y., Zhou, Y., & Xie, B. (2015). A Novel Thermal Sensor for the Sensitive Measurement of Chemical Oxygen Demand. Sensors, 15(8), 20501–20510.

Zhang, C., Su, H., & Tan, T. (2013). Batch and semi-continuous anaerobic digestion of food waste in a dual solid-liquid system. Bioresource Technology, 145, 10–16.

Zhang, C., Su, H., Baeyens, J., & Tan, T. (2014). Reviewing the anaerobic digestion of food waste for biogas production. Renewable and Sustainable Energy Reviews, 38, 383–392.

# APPENDICES

## APPENDIX 1: RESEARCH OUTPUT

Associated with this work are some publications done. A review paper was published with the Renewable and Sustainable Energy Reviews Journal under Elservier and another was published in the European Biomass Conference and Exhibition Proceedings. Two more papers have been submitted for review and three presentations have been done at conferences. Appendices 1.2 - 1.5 give the list of this research output.

### APPENDIX 1.1: Journal Publications

Mutungwazi, A., Mukumba, P. and Makaka, G. (2018) ‘Biogas digester types installed in South Africa: A review’, Renewable and Sustainable Energy Reviews. Pergamon, pp. 172–180. doi: 10.1016/j.rser.2017.07.051.

### APPENDIX 1.2: Conference Proceedings

Mukumba P., Makaka G., Mamphweli S., Mutungwazi. A. (2017) ‘25th European Biomass Conference and Exhibition, 12-15 June 2017, Stockholm, Sweden’, in, pp. 12–15.

### APPENDIX 1.3: Conference Presentations

A. Mutungwazi, P. Mukumba, G. Makaka, Contribution ID: 316: Design, construction and performance evaluation of a greenhouse temperature regulated, agitated portable biogas digester. SAIP conference, Tuesday 04 Jul 2017 at 17:10 (01h50'), Stellenbosch University, Stellenbosch, South Africa.

A. Mutungwazi, P. Mukumba and G. Makaka, Department of Physics, University of Fort Hare, Alice VC6–30: Design of a greenhouse regulated temperature, portable biogas digester (M), Renewable and Sustainable Energy Post Graduate Symposium, 4-6 September 2016, University of Fort Hare, Alice, South Africa.

A. Mutungwazi, P. Mukumba, G. Makaka, Design, construction and performance evaluation of a greenhouse regulated temperature biogas digester, Sasol University Research Seminar, Thursday 2 November 2017, Sasol Place, Sandton, Johannesburg, South Africa.

## APPENDIX 1.4: Submissions for Journal Publication

A. Mutungwazi, P. Mukumba, G. Makaka, Design, construction and performance evaluation of a greenhouse regulated temperature biogas digester, International Journal of Engineering Research and Technology, 2017.

## APPENDIX 1.5: Submissions for Conference Proceedings Publication

A. Mutungwazi, P. Mukumba, G. Makaka, Design of a greenhouse temperature regulated, agitated portable biogas digester, South African Institute of Physics, 2017.

## APPENDIX 1.6: Summary of Information

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|---|---|
| Papers published with accredited Journals | 1 |
| Papers submitted for publication with accredited Journals | 1 |
| Papers published in Conference Proceedings | 1 |
| Papers submitted for publication in Conference Proceedings | 1 |