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- **MASTERS DISSERTATION -**

EXPERIMENTAL INVESTIGATION OF BIOGAS PRODUCTION FROM FEEDLOT CATTLE MANURE

By

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Abbreviations and Symbols

Abbreviations	Description
AD	Anaerobic digestion
AOAC	Association of Official Agricultural Chemists
BMP	Biochemical methane potential
CHP	Combined heat and power
CP	Crude protein – nitrogen content
CSP	Concentrated solar power
CSTR	Continuously stirred tank reactor
GC	Gas chromatograph
HRT	Hydraulic retention time
IRR	Internal Rate of Return
NERSA	National Energy Regulator of South Africa
NPV	Net Present Value
Nml/g.VS	Normal millilitres per gram volatile solids
ODM	Organic dry matter
PV	Photovoltaics
REFIT	Renewable energy feed-in tariff
ROI	Rate on Return
TS	Total solids – organic and inorganic
US$	United States of America Dollar
VFA	Volatile fatty acids
VS	Volatile solids – organic compound (sample less the ash)
ZAR	South African Rand

Symbols	Description	Units
A	Cross-sectional area to flow	m^2
A_{BD}	Total surface area of biogas digester that conducts heat	m^2
B_{BD}	Volume loading rate of volatile solids into biogas digester	$kg_{VS}\ m^{-3}d^{-1}$
C	Carbon	-
c	Concentration	mol m^{-3}
Cp_{su}	Specific heat capacity of substrate	kJ $kg^{-1}K^{-1}$
D_{BD}	Diameter of biogas digester	m
D_{DP}	Diameter of biogas digester discharge pipe	m
D_H	Diameter of heating pipe	m
D_{PA}	Diameter of propeller agitator	m
D_{PT}	Diameter of preparation tank	m
D_R	Diameter of residue storage tank	m
E_B	Energy content of biogas	kWh m^{-3}
E_{CHP}	Nominal capacity of engine	kW

E_{el}	Total electrical power consumption	kW
E_{oil}	Energy content of ignition oil	kWh kg^{-3}
E_{th}	Total heat consumption	kW
E_{tot}	Total energy yield of biogas	kW
ΔG_f	Gibbs free energy	kJ mol^{-1}
g	Gravitational constant	m s^{-2}
H_{BD}	Height of biogas digester	m
H_{PT}	Height of preparation tank	m
H_R	Height of residue storage tank	m
K_B	Annual costs for concrete works	US$ a^{-1}
K_{cap}	Total annual capital bound costs	US$ a^{-1}
K_{CHP}	Annual costs for CHP	US$ a^{-1}
KE_{el}	Electrical energy yield	kW
K_{el}	Annual cost for electricity	US$ a^{-1}
KE_{th}	Thermal energy yield	kW
K_{HE}	Annual costs for heating	US$ a^{-1}
K_{int}	Annual costs for interest	US$ a^{-1}
K_{inv}	Initial investment	US$
K_{io}	Cost of ignition oil	US$ kg^{-1}
K_k	Additional costs of CHP	US$
KM_{CHP}	Annual maintenance costs for CHP	US$ a^{-1}
KM_{conc}	Annual maintenance costs for concrete works	US$ a^{-1}
KM_{ins}	Annual insurance costs	US$ a^{-1}
KM_{pers}	Annual personnel costs	US$ a^{-1}
KM_{tech}	Annual maintenance costs for technical equipment	US$ a^{-1}
KM_{tot}	Total operational costs of the biogas plant	US$ a^{-1}
KO_{tot}	Overall annual costs of the biogas plant	US$ a^{-1}
K_{oil}	Annual cost for ignition oil	US$ a^{-1}
KP_{el}	Annual sales of electrical power	US$ a^{-1}
KP_{fert}	Annual sales of digestate as fertilizer	US$ a^{-1}
KP_{HE}	Annual sales of heat power	US$ a^{-1}
KP_{rev}	Annual revenue of the biogas plant	US$ a^{-1}
KP_{tot}	Annual income of the biogas plant	US$ a^{-1}
K_{pers}	Personnel rate per hour	US$ h^{-1}
K_{REFIT}	Government subsidy for the sales of biogas electrical power	US$ kWh^{-1}
K_{run}	Annual costs of running the biogas plant	US$ a^{-1}
K_{sum}	Average summer megaflex tariff	US$ kWh^{-1}
K_T	Annual costs for technical equipment	US$ a^{-1}
K_{tot}	Total investment	US$
K_{win}	Average winter megaflex tariff	US$ kWh^{-1}
KW_{spec}	Cost for heating	US$ kWh^{-1}
k	Permeability	m^2

k_{BD}	k-factor of biogas digester	W $m^{-2}K^{-1}$
k_H	k-factor of heating pipe	W $m^{-2}K^{-1}$
L_H	Length of biogas digester heating pipe	m
$\dot{M}_B$	Biogas flow rate	Kg d^{-1}
$\dot{M}_G$	Cattle manure yield per day	Kg d^{-1}
$\dot{M}_{oil}$	Ignition oil flow rate	Kg d^{-1}
N	Nitrogen	-
$\mathfrak{Ne}$	Newton Number	-
n_{PA}	Speed of propeller agitator	Rev min^{-1}
$\nabla\mathbf{P}$	Pressure gradient vector	Pa m^{-1}
P_{PA}	Rated power of propeller agitator	kW
$(P_{PA})_{tot}$	Total power consumption of propeller agitator	KW
ΔP_{VP}	Preparation tank pressure head	kPa
$(P_{VP})_1$	Pump motor capacity to deliver manure to the biogas digester	kW
$(P_{VP})_2$	Pump motor capacity to drain the volume of the biogas digester	kW
Q_{loss}	Heat loss of biogas digester	kW
Q_{su}	Heat required for heating the substrate of the biogas digester	kW
Q_{tot}	Total required heat	kW
rpm	Revolutions per minute	
S_{BD}	Polystyrene insulation thickness of biogas digester	m
T_A	Lowest outside temperature in (humid soil) winter	°C
T_{BD}	High temperature of biogas digester	°C
T_{HE}	Inlet temperature of heating medium (water)	°C
T_{HA}	Outlet temperature of heating medium (water)	°C
ΔT_H	Temperature difference between heating medium and substrate	K
ΔT_{su}	Temperature difference of substrate to be heated	K
ΔT_w	Temperature difference of heating medium (water)	K
$t_{80\%}$	Time to produce 80% of the maximum biogas	d
t_B	Time for concrete works to amortize	y
t_{BD}	Substrate residence time in the biogas digester	d
t_{BD1}	Time to empty the complete volume of the biogas digester	h
t_K	Time for cost of CHP to amortize	y
t_{PA}	Propeller agitator working time	min h^{-1}
t_{pers}	Annual working hours of personnel operating the biogas plant	h a^{-1}
t_{PT}	Time liquid manure is produced and stored in preparation tank	d
t_R	Residue storage time	d
t_S	Annual operational hours of biogas plant	h a^{-1}
t_T	Time for technical equipment to amortize	y
t_{VP}	Time to pump the complete volume of the biogas digester	h
V_{BD}	Volume of biogas digester	m^3
V_G	Volume of gasholder	m^3
V_{PT}	Volume of preparation tank	m^3

V_R	Volume of residue storage tank	m^3
VS_{BD}	Biogas digester VS yield per day	$kg_{VS}\ d^{-1}$
$\tilde{V}_{BD}$	Daily biogas yield from cattle manure	m^3d^{-1}
$\tilde{V}_R$	Water reverted back to biogas digester from residue tank	m^3d^{-1}
$\tilde{V}_{VP}$	Manure pumping flow rate of preparation tank	m^3h^{-1}
$(\tilde{V}_{VP})_1$	Pump throughput	m^3h^{-1}
$\tilde{V}_w$	Heating liquid flow rate	m^3h^{-1}
Z_R	Interest rate	%
f_{BD}	Biogas digester tank air fixtures factor	-
f_{PT}	Preparation tank air fixtures factor	-
f_R	Residue storage tank air fixtures factor	-
y_B	Percentage of investment for maintenance of concrete works	%
y_{CHP}	Percentage of total investment for CHP	%
y_{ins}	Percentage of total investment for insurance	%
y_T	Percentage of total investment for technical equipment	%
α_{BD}	Polystyrene heat transfer coefficient	$W\ m^{-1}K^{-1}$
$(\alpha_H)_i$	Inside heat transfer coefficient of heating pipe	$W\ m^{-1}K^{-1}$
$(\alpha_H)_o$	Outside heat transfer coefficient of heating pipe	$W\ m^{-1}K^{-1}$
α_i	Heat transfer coefficient of wet agitated liquid in the digester	$W\ m^{-1}K^{-1}$
α_o	Heat transfer coefficient of humid soil	$W\ m^{-1}K^{-1}$
η_{el}	Electrical efficiency of diesel engine	%
η_{th}	Thermal efficiency of diesel engine	%
η_{VP}	Preparation tank pump efficiency	%
μ	Viscosity	Pa s
ρ	Density	$kg\ m^3$
ρ_B	Density of biogas	$kg\ m^{-3}$
ρ_G	Density of cattle manure	$kg\ m^{-3}$
ρ_w	Density of water	$kg\ m^{-3}$
υ	Fluid velocity	$m\ s^{-1}$
υ_H	Heating medium velocity	$m\ s^{-1}$
ϕ	Species flux	$m\ s^{-1}$
χ_B	Proportion of investment used for concrete works	-
χ_T	Proportion of investment used for technical equipment	-

Abstract

The demand for alternative power sources has increased rapidly over the past few years as the cost of electricity is rapidly increasing in South Africa. Biogas can be generated from biomass in an anaerobic digestion process and used to generate electricity and heat as an alternative energy source to fossil fuel generated electricity. This study is focused on the biogas generation from cattle manure. The manure was analysed for weight loss over 40 days and the energy content determined. The biogas volume produced was measured as a function of time until there was no measurable gas formation after 41 days. The biogas was analysed for methane and carbon dioxide content using a gas chromatograph. A techno-economic model was developed in terms of the design of a simple agricultural biogas plant and the economics of the plant.

The same manure sample was divided into different sub-samples to be aged to 0, 4, 7, 11, 14, 21, 28, 35 and 40 days respectively and these were analysed using the biochemical methane potential test. The corresponding cumulative biogas yield was 217, 206, 199, 154, 208, 208, 245, 369 and 295 Nml/g.VS respectively. The test results showed that an average of 240 Nml/g.VS of biogas can be produced from cattle manure that is less than 40 days old, with an average methane and carbon dioxide percentage of 63 % and 31 % respectively. Within 3 to 4 days the manure samples generated 80 % of the potential final biogas volume.

The design of the biogas plant was based on 7 000 cattle that would produce 58 330 kg manure per day. The average biogas yield of 240 Nm^3/ton.VS was assumed, together with the average TS and VS content of 17% and 80% (as a % of TS) respectively as experimentally determined. The designed total power yield of the biogas plant was 555.3 kW for the CHP. The electrical power of 166.6 kW would be produced from a 220 kW engine and the heat energy produced was 277.7 kW. The total electrical and heat power consumption of the biogas plant was designed to be 5.0 kW and 90.7 kW respectively.

The economic viability of the biogas plant was based on a proposed REFIT value of US$ 0.0926 (R1.39) per kWh for the sales of electrical energy generated from biogas. The annual capital, consumption and operational costs of the biogas plant was calculated to be US$ 33 200, US$ 16 617 and US$ 16 209 respectively. The total annual income and costs of the biogas plant was US$ 140 133 and US$ 66 026 respectively. This leads to a net annual revenue of US$ 74 107 for the biogas plant. The return on investment was calculated to be 30.6% (>13%) and is attractive from the commercial point of view and will enter the economic potential. The net present value and internal rate of return was calculated to be US$ 542 792 and 30.4% respectively with a payback time of 3.3 years. Thus the biogas plant would therefore be economically viable in South Africa.

CHAPTER 1: Introduction

1.1 Background

Fossil fuel is currently the world's main source of energy and is prevalent in forms such as crude oil, lignite, hard coal and natural gas. Such fuels are not renewable energy sources as they were formed over hundreds of millions of years but are consumed at a much faster rate than the rate at which new fossil fuels are being formed [1]. One of the largest disadvantages associated with the use of fossil fuels is that harmful greenhouse gasses such as carbon dioxide are released when it is burnt during energy production processes. This is especially true during the production of electricity via coal-fired power plants. Biogas on the other hand is a renewable energy source because it can be produced continuously from biomass (organic material), which is a living storage of solar energy through photosynthesis.

Biogas is formed during the anaerobic breakdown of biomass by micro bacteria. This biological breakdown is a natural process that occurs when biomass is decomposed via a group of microorganisms which are metabolically active in humid conditions in the absence of oxygen [2]. Such a process is often referred to as Anaerobic Digestion (AD). After AD the remaining product called digestate can be used as an excellent source of fertilizer because of its high nutrient value. Biogas is generally a mixture of different gasses, with methane being the largest constituent (50-75% by volume) followed by carbon dioxide (25-45% by volume), and other gaseous components (less than 7% by volume). Biogas with a methane content of 45% and higher is flammable and can be used to produce clean energy [2].

When consumed during power production both biogas and fossil fuels release carbon dioxide as a by-product of combustion. The main difference is that the carbon in biogas was recently taken up from the atmosphere, by photosynthetic activity. Therefore, the carbon cycle of biogas is much shorter (between one and seven years) than that of fossil fuel (millions of years). Besides the environmental advantageous impact of biofuels, the relatively fast depletion of the world's fossil fuel supplies makes it necessary for humans to investigate biogas usage as an alternative energy source.

South Africa is rich in agricultural feedlots, in particular cattle feedlots. Each feedlot is unique in terms of the quality and characteristics of the manure. Fully grown cattle can produce an average of 20 kg of manure per head per day of which 4 kg is Total Solids (TS) and 13% of the fresh manure is Volatile Solids (VS). Cattle manure has the capacity to generate 200 to 500 litres of biogas per kg of dry manure depending on the process characteristics [3].

The manure on cattle feedlots is scraped out of the stalls and piled on large heaps or placed in storage pits daily, where the manure is exposed to the elements of nature, such as rain, wind and sunlight. The manure on the heaps or in the storage pits ranges from fresh manure to aged (or dried) manure. While the manure is on the heap or in the storage pit it undergoes some aerobic digestion and the manure loses some of its energy content that can potentially be used to produce biogas.

The first attempt to use biogas as a renewable energy source was in Exeter, England in 1897, when streetlamps were run on gas obtained during the AD of wastewater [2]. The technology of using AD to produce biogas from waste materials is rapidly developing as the price and demand of electricity increase. Biogas digesters are being used all around the world to produce biogas. Countries like Germany, Denmark, United Kingdom, China and India use biogas generated from waste to generate electricity and for gas burners.

The cost and demand for electricity is very high in South Africa, due to the rapidly increasing population size that consumes more electricity than can be generated. This calls for new and innovative methods to generate electricity to keep up with the demand. Biogas is an energy source that can be used to reduce the electricity load of fossil fuel power stations.

The construction of large biogas plants is expensive. It is therefore necessary to do a techno-economical study on the production of biogas. This will give a good estimate of the amount of biogas that can be produced from a given amount of cattle manure. The AD process can be studied in a cheap and economical manner for process behaviour through the Biochemical Methane Potential (BMP) test. Based on the results of the quality and quantity of the biogas, a conclusion can be drawn if it is economical to build a biogas plant to produce electricity. This study will give an indication of the impact of manure aging on the economics of biogas production

1.2 Problem Statement

1.2.1 Manure aging and depletion of volatile solids

In South Africa both water and energy are scarce natural resources. Feedlot cattle manure is a mixture of materials which contain large amounts of water and organic materials. This makes it a very suitable feedstock for anaerobic fermentation for biogas production. This process requires a wet organic feed mixture with less than 15% total organic solids [1].

Fresh cattle manure contains about 80% water, 15% organic material and 5% inorganic materials. In normal feedlot operations, the manure builds up as a layer on the floor of the feedlot before it is removed; this causes the manure to lose valuable water and energy. As manure ages, more than 80% of the water and about 50% of the organic matter is lost over a timescale of months as the manure is broken down [2].

As a result, significant amounts of water have to be added for biogas production in the anaerobic fermentation process when aged manure is used as feedstock. Both water and organic matter have a significant impact on the economy of biogas production. Although biogas production from cattle manure has been studied in other countries (Europe), such techno-economic studies done in other countries cannot necessarily be applied to conditions in South Africa.

Manure can be considered as a matrix of organic fibres, in between which a watery solution with organic materials is present. During the drying process, a drying front travels inwards through the material. On the inside the manure is still wet and on the outside a dry layer of manure is formed, which forms a porous medium with typical porosity of 80% and typical pore sizes of 1mm. Most of the relevant transport processes take place in this dried porous medium.

Normally, transport in porous media can be described by the Darcy equation [4]:

$$\upsilon = -\frac{\mathrm{k}}{\mu}(\nabla\mathbf{P} - \rho\mathbf{g})$$

$$\Phi = \mathrm{A}\upsilon\mathrm{c}$$

Where υ is the fluid velocity, k is the permeability, μ is the viscosity of the fluid, $\nabla\mathbf{P}$ is the pressure gradient vector, ρ the density, $\mathbf{g}$ the gravitational constant, Φ the species flux, A the cross-sectional area to flow and c the concentration. The drying front model, although confirmed by observations, is however not capable of completely describing the mass transfer process within the manure. The same holds for the convection-diffusion equation [4]:

$$\frac{\partial c}{\partial t} = \nabla \cdot (\mathrm{D}\nabla\mathrm{c}) - \nabla \cdot (\upsilon\mathrm{c})$$

Both have a linear, parabolic or hyperbolic solution, which does not match experimental observations [4]. A likely reason is that not all of the volatile species (water and organic compounds) are freely accessible for transport; a significant part has to be released or converted through chemical or biochemical reactions [2]. These reactions can be monitored through the formation of biogas in the BMP test.

1.2.2 Biogas Production

The biogas yield from any bio-digestible organic compound depends on the amount of VS contained within the biomass. Theoretically fresh cattle manure should produce more biogas than aged cattle manure, due to its high VS when compared to aged cattle manure. The optimum TS concentration for biogas formation is between 6 % and 7 % within the digester [2]. This requires the addition of water to the cattle manure when charging the digester. Fresh cattle manure contains a lot more water than aged cattle manure. This means that aged cattle manure requires more water addition than fresh manure in order to dilute the manure to the optimum TS concentration for biogas production in the AD process.

Fresh cattle manure already contains the anaerobic bacteria that produce biogas, as these are generated in the digestive tract of the animals. When the cattle manure is exposed to oxygen and fluctuations in temperature outside the animal digestive tract, the concentration of bacteria decreases as the fresh manure becomes more aged. There is thus a difference between fresh cattle manure and aged cattle manure in terms of VS, TS, nutritional value and the anaerobic bacterial content that produces biogas.

In order to determine the impact of aging of manure on AD parameters, fresh cattle manure and aged cattle manure must therefore be compared with each other in terms of biogas yield, biogas quality and hydraulic retention time (HRT) required for optimum biogas production. These parameters can then be used in the design of a large-scale biogas plant. By analysing the biogas yield over a period, for fresh and aged manure, the required HRT can be determined experimentally. The HRT then determines the rate at which the biogas digester is fed to extract the maximum amount of biogas from the biomass before it is removed from the digester.

A method of estimating the ultimate conversion of biomass into usable energy is the BMP test. The BMP test determines the amount of stored energy that can be extracted from a mass of biomass in the form of flammable methane gas [5]. The BMP test method suggests the addition of inoculants in the form of sewage sludge or rumen fluid to speed up the AD process [6].

Sewage sludge can be found in any anaerobic water treatment plant. The rumen fluid is found in one of the four compartments of a cow's stomach. The ecosystems in the rumen fluid consists of the bacteria ($10^{10} – 10^{11}$ cells per ml) required for anaerobic digestion. The optimum temperature to perform the BMP test under mesophilic conditions is 35°C [2].

1.2.3 Techno-economics of a farm scale biogas digester

The number of domestic animals and the area available for the cultivation of co-ferments determines the size of an agricultural biogas plant [2]. The design of agricultural biogas plants is therefore dependent on the number of animals available on the farm that produce feedstock for the biogas digester. The basic equipment of a simple agricultural biogas plant can be designed on the basis of the daily biogas rate and can consist of the following:

- Preparation tank
- Preparation tank pump
- Biogas digester
- Digester heating pipes and pump
- Biogas holder
- Biogas Engine
- Storage tank for residue

Biogas plants have high investment demands and thus the financial viability of biogas projects is dependent on financial aid from investors. The financing scheme of a biogas plant is in general offered at low interest rates and longer terms. The key operational cost for biogas plants includes the following but is not limited to [1]:

- The working hours of staff (maintenance and feeding the system)
- Maintenance cost of the biogas plant (% of the investment/year)
- Operational cost of CHP (Combined Heat and Power) if there is a market for both power and waste heat
- The biogas plant's own electrical demand (kWh/year)
- Insurance costs (% of the investment/year)

The feed in tariffs for the supply of electricity from biogas plays an important role in the revenue of the biogas plant and is determined by the utility, in the case of South Africa by the government through the state-owned enterprise Eskom. The revenue of the biogas plant can be increased by using/selling the waste heat energy from the internal combustion engine used for electricity generation and by selling the digestate as fertiliser. The Internal Return Rate (IRR) of the project should be higher than 9% to consider the project to be economically viable [1]. The annual capital costs, annual cost of running and operational cost should be determined and subtracted from the annual income to predict the annual revenue of the biogas plant.

1.3 Research Objectives

The overall aim of this dissertation was to use the BMP test to investigate the biogas yield from fresh cattle manure and aged cattle manure through the process of AD. The manure aging process was monitored in terms of weight loss and for drying front formation (top dry layer of manure that forms as manure dries). Each manure sample was analysed for TS, VS and Crude Protein (CP) to analyse the energy potential of the cattle manure. The manure energy potential in terms of VS will determine the amount and quality of the biogas formed during the AD process. The objective of the research is to investigate:

1) The drying process of cattle manure
2) The amount of weight and nutrients lost as manure ages in the open air
3) The TS, VS and CP as a function of aging time
4) The anaerobic digestion of cattle feedlot manure ranging from fresh manure to aged manure to examine:
    (i) The changes in manure composition in terms of changes in volatile solids and crude protein within the manure as manure is aged.
    (ii) The system performance in terms of biogas yield (Nml/g.VS).
    (iii) The quality of the biogas produced in terms of percentage methane and carbon dioxide.
    (iv) To determine the biogas evolution as a function of time to determine the optimum design point for biogas digester designers.
    (v) The difference in biogas yield between frozen manure samples and unfrozen manures samples.
5) Use the experimental results to carry out a techno- economic case study

1.4 Conclusion

Biogas is produced naturally through the AD process by anaerobic bacteria that break down biomass. The biomass loses some of its energy content as it is exposed to the environment and decomposes. The biomass also loses moisture as it is exposed to the environment. The BMP test was developed to determine the ultimate methane yield of a specific biomass. The produced biogas volume and quality in terms of methane and carbon dioxide percentages is determined by the amount of VS within the manure. Chapter 2 that follows describes the theoretical foundation of biogas production from biomass and the process of AD.

CHAPTER 2: Theoretical foundation

2.1 Introduction

Cattle feedlots generate large quantities of waste that can be used as renewable energy sources when converted into biogas. One of the usable wastes on cattle feedlots is cattle manure that has a high nutrient content. The cattle manure can be used to feed a biogas digester to produce biogas in an AD process. The biogas is used predominantly for heat and electricity generation, but it can also be applied as a vehicle fuel or for hydrogen production which is necessary for fuel cells [7].

The boilers and gas turbines require a certain amount and quality of biogas to operate efficiently to produce heat and electricity respectively. By analysing the biogas yield from fresh manure and aged manure, it can be confirmed what type of manure will yield the most biogas in terms of volume and quality. This will give an indication of what type of manure to feed into a biogas digester and produce enough biogas to make the process economical. The difference in biogas yield between fresh and aged manure will therefore determine at what stage it is no longer economical to produce biogas from the manure.

Cattle manure is a favourable feedstock for AD due to its high nutrient content and because the cattle manure already contains the biogas-forming bacteria when the manure is still fresh [2]. When most of the volatile organic compounds have been extracted from the cattle manure in the AD process and converted into biogas, the remaining substrate from the digester can be used as fertiliser, because of its remaining nutrient content [1].

Biogas can be generated from any organic waste with a suitable volatile solids content through AD under certain process parameters. The composition of the biogas depends on the chemical composition of the feedstock that went through the process of AD. The conditions in which AD can take place include parameters such as temperature, pH levels, organic loading rate and HRT [2].

The number of days required for the AD process to produce 80% of the maximum biogas volume can be used as an indication of how long the substrate should be kept in the digester; this is common practice in laboratory biogas analysis (Talbot & Talbot Laboratories) [8]. The biogas evolution as a function of time was used as a guideline for optimisation of the process of AD. The HRT determines the rate at which the biogas digester must be fed. It is thus the average time interval that the substrate is kept in the digester. The HRT is the quotient of the digester volume and the volume of substrate fed into the digester per time unit [1]. By analysing the biogas yield over a period, for fresh and aged manure, the required HRT can thus be determined experimentally.

The most common agricultural biomass that is used as substrate (feedstock) in biogas digesters is animal manure, because of its natural content of anaerobic bacteria, high energy content, high water content, low cost and high availability [2]. Cattle manure consists of solids and water. The TS is the sum of the organic compounds and the inorganic compounds while the VS only consists of organic compounds. The VS is given as a percentage of the TS or as a percentage of the entire sample. Figure 1 illustrates the manure sample with its water content, TS and VS as a percentage of the total manure sample. Fresh cattle manure has relatively high water and VS content.

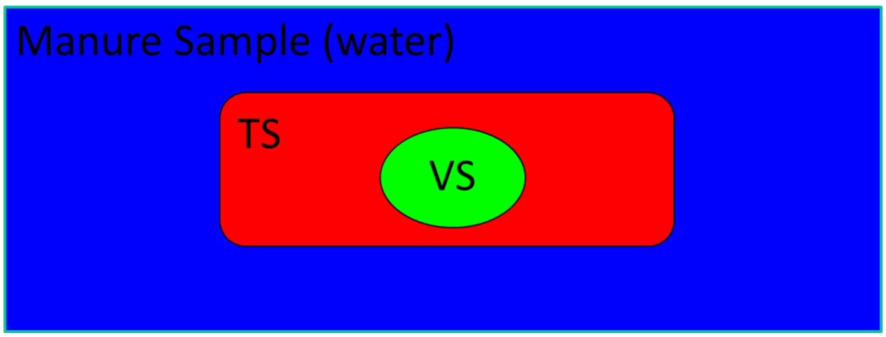

Figure 1: Illustration of the TS and VS of a sample of manure

Cattle manure can be made up of a wide range of TS and VS, depending on the freshness of the manure and the feed that the cattle receive. The amount of VS in the manure determines the biogas yield from the AD process to produce methane gas [2]. Biogas is a mixture of a wide range of gasses but the main constituents are methane (50 – 75 %) and carbon dioxide (25 -45 %) as illustrated in table 1 below [1].

Table 1: Composition of biogas

Gas	Chemical symbol	Content (volume %)
Methane	CH_4	50 - 75
Carbon dioxide	CO_2	25 - 45
Water vapour	H_2O	2 - 7
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

2.2 The biochemistry of the anaerobic digestion process

The formation of methane, ammonia, hydrogen sulphide and carbon dioxide follows in general the following equation when biomass is chemically broken down to produce biogas [2]:

Equation 1

$$\mathrm{C_cH_hO_oN_nS_s} + y.\mathrm{H_2O} \rightarrow x.\mathrm{CH_4} + n.\mathrm{NH_3} + s.\mathrm{H_2S} + (c-x).\mathrm{CO_2}$$

Where

$$x = \frac{1}{8}(4c + h - 2o - 3n - 2s)$$

$$y = \frac{1}{4}(4c - h - 2o + 3n + 2s)$$

The building blocks from which biogas is produced include carbohydrates, fats and proteins as given by the following equation:

Equation 2

$$\text{Carbohydrates: } \mathrm{C_6H_{12}O_6} \rightarrow 3\mathrm{CO_2} + 3\mathrm{CH_4}$$

$$\text{Fats: } \mathrm{C_{12}H_{24}O_6} + 3\mathrm{H_2O} \rightarrow 4.5\mathrm{CO_2} + 7.5\mathrm{CH_4}$$

$$\text{Proteins: } \mathrm{C_{13}H_{25}O_7N_3S} + 6\mathrm{H_2O} \rightarrow 6\mathrm{CO_2} + 6.5\mathrm{CH_4} + 3\mathrm{NH_3} + \mathrm{H_2S}$$

Some of the sulphur binds with hydrogen to form H_2S while some remains in the residue of the digestate. A part of the carbon dioxide molecules binds to the ammonia molecules. The theoretical CH_4:CO_2 ratio of biogas is 71%:29%, but the actual ratio of methane to carbon dioxide is highly dependent on the composition of the biomass used in the AD process. The following steps give an indication of the Gibbs free energy balance when biogas is produced. The energy is originally captured during photosynthesis and stored in the organic biomass as portrayed in the following steps [2].

Equation 3

$$\mathrm{CO_2} + \mathrm{H_2O} + \text{“solar energy”} \rightarrow \mathrm{CH_2O} + \mathrm{O_2}$$

$$Carbon\ dioxide + Water + \text{“}solar\ energy\text{”} \rightarrow Carbohydrate + Oxygen$$

$$(-394\ \mathrm{KJ}) + (-273\ \mathrm{KJ}) + \Delta\mathrm{G_f} \rightarrow (-153\ \mathrm{kJ}) + 0\ \mathrm{kJ}$$

$$\Delta\mathrm{G_f} = +\ 478\ \mathrm{KJ/mol} \qquad \text{(At a pH of 7)}$$

Where ΔG_f refers to Gibbs free energy change

The following Gibbs free energy balance equation illustrates the release of energy and the degradation of organic biomass into biogas [2].

Equation 4

$$\text{Carbohydrate: } CH_2O \rightarrow 0.5CH_4 + 0.5CO_2$$

$$(-153\ \text{KJ}) + \Delta G_f \rightarrow 0.5(-51\ \text{kJ}) + 0.5(-394\ \text{KJ})$$

$$\Delta G_f = -70\ \text{KJ/mol}$$

The solar energy stored through photosynthesis is released through the combustion of methane and oxygen that produces carbon dioxide and water as products [2].

Equation 5

$$0.5CH_4 + O_2 \rightarrow 0.5CO_2 + H_2O$$

$$0.5(-51\ \text{KJ}) + 0\ \text{KJ} + \Delta G_f \rightarrow 0.5(-394\ \text{kJ}) + (-237\ \text{KJ})$$

$$\Delta G_f = -408\ \text{KJ/mol}$$

This closes the energy loop of the AD process. AD bio-reactions release very little heat during the fermentation process, thus the digester must be heated and thermally well-insulated. Theoretically the energy that is released during the combustion of biomass corresponds to the sum of the energy set free in the production of biogas plus the burning of methane. This energy is equal to the energy that was needed for photosynthesis. In practice the volume of biogas that can be obtained from substrate is determined by [2]:

- The fraction of material with high energy content within the biomass
- The TS content of the substrate
- The VS content of organic dry matter
- The methane content of the substrate
- The actual degree of decomposition in the respective biogas plant.

2.3 The biochemical process of anaerobic digestion

The four anaerobic processes of hydrolysis, acidogenesis, acetogenesis and methanogenesis run simultaneously in the biogas digester. During the first step of hydrolysis small amounts of biogas are formed and biogas generation increases until it reaches its peak during the fourth step of methanogenesis. Figure 2 shows a simplified diagram of the biochemical process of AD [1].

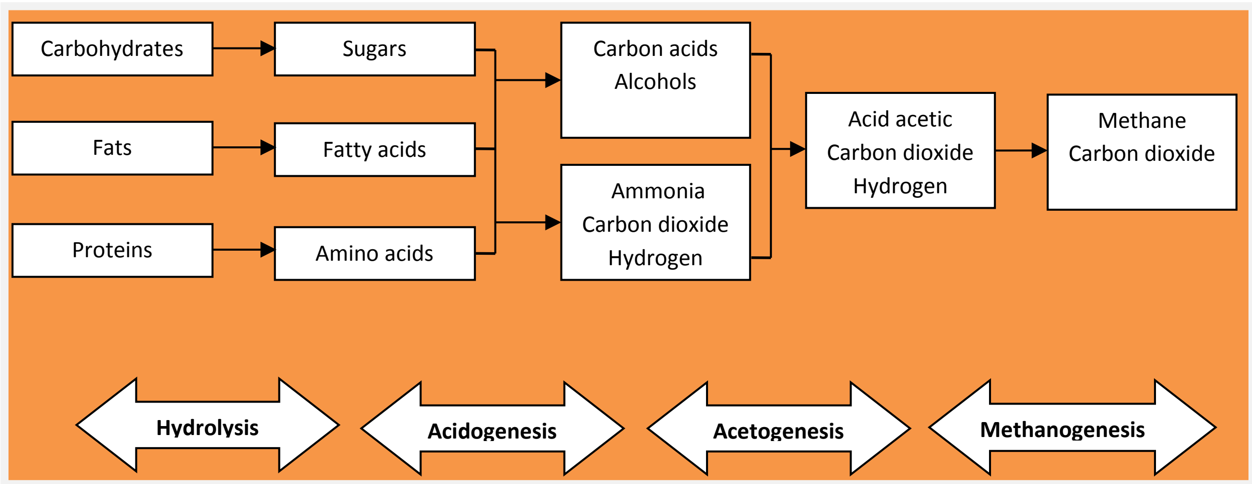

Figure 2: The main process steps of AD

2.3.1 Hydrolysis

Hydrolysis is the first step in the AD process. In this process, complex organic matter is broken down into smaller units of organic matter. During hydrolysis, polymers like carbohydrates, lipids, nucleic acids and proteins are converted into glucose, glycerol, purines and pyridines. The hydrolytic microorganisms excrete hydrolytic enzymes that convert the biopolymers into simpler and soluble compounds [1]. The enzymes from facultative and obligatory anaerobic bacteria both drive the process of hydrolysis. The hydrolysis of carbohydrates is complete within a few hours whereas the hydrolysis of proteins and lipids takes a few days. The oxygen dissolved in water is used up by the facultative anaerobic microorganisms; this then produces the low redox potential required by the obligatory anaerobic microorganisms [2].

2.3.2 Acidogenesis

The acidogenic bacteria with fermentative properties convert the products of hydrolysis into methanogenic substrate. During acidogenesis, simple sugars, amino acids and fatty acids are degraded into acetate, carbon dioxide and hydrogen (70%) as well as into volatile fatty acids and alcohols (30%) [1]. The intermediately formed hydrogen ion concentration influences the fermentation products. The higher the partial pressure of the hydrogen, the fewer reduced compounds are produced and the slower the reaction rate of AD [2].

2.3.3 Acetogenesis

The methanogenic bacteria cannot directly convert the products from acidogenesis into methane. Therefore the products from acidogenesis are converted into methanogenic substrates during acetogenesis. During this process the production of hydrogen increases the hydrogen partial pressure. This then inhibits the metabolism of the acetogenic bacteria. In the last step of methanogenesis, the hydrogen is then converted into methane. Acetogenic bacteria are obligatory hydrogen producers. When the hydrogen partial pressure is low the acetogenic bacteria form hydrogen, carbon dioxide and acetate predominantly. When the hydrogen partial pressure is high the acetogenic bacteria form butyric, capronic, propionic, and valeric acids and ethanol predominantly [1]. Only hydrogen, carbon dioxide and acetate can be processed by the methanogenic bacteria. About 30% of the entire methane production in the AD process is due to the reduction of carbon dioxide to methane by hydrogen. At the same time during acetogenesis, organic nitrogen and sulphur compounds are reduced to hydrogen sulphide and ammonia by the hydrogen ions [2].

2.3.4 Methanogenesis

The methanogenic bacteria form methane and carbon dioxide from the products of previous steps. Acetate forms 70% of the methane while the other 30% is produced by converting hydrogen and carbon dioxide into methane. Methanogenesis is the slowest biochemical reaction of the AD process and is severely influenced by operational conditions. These operational conditions are feeding rate, temperature and pH levels. Methane production can be terminated by overloading the digester, temperature changes, pH variations or excessive oxygen in the digester [1]. Over-acidification can occur during acetogenesis and inhibit the formation of methane. This over-acidification occurs when the hydrogen forms acids like hydrogen sulphide instead of methane. Acetate-using methanogenic bacteria grow very slowly in acetate, with a theoretical reaction time of at least 100 hours [1].

2.4 The process parameters of anaerobic digestion

There are some crucial process parameters that effect the performance and efficiency of the AD process. These parameters must be closely monitored and kept constant to ensure that AD results in optimal biogas production. The anaerobic microorganisms that produce biogas are sensitive to changes in operating conditions which can affect their growth and activity. The process parameters of AD are temperature, pH levels, mixing, HRT, concentration of microorganisms, volatile fatty acids, ammonia concentration and specific surface area of biomass.

2.4.1 Temperature

There are three temperature ranges in which AD can take place. Each temperature range has its own characteristics and required retention time in terms of biogas production rate. The table below indicate that there is a direct relation between the process temperature and the required retention time of the biomass [1].

Table 2: Process temperature and typical retention time

Thermal stage	Process temperature (°C)	Retention time (days)
Psychrophilic	Less than 20	70 to 80
Mesophilic	30 to 42	30 to 40
Thermophilic	43 to 55	15 to 20

The operational temperature is selected based on the type of biomass used. This temperature is generally kept constant in the digester through a floor or wall heating system. The anaerobic bacteria that produce biogas are extremely sensitive to changes in temperature and this can negatively affect biogas production. The methane content increases with an increase in the digestion temperature, but only to a small degree. According to Chae et al [9], the optimal temperature to produce biogas under mesophilic conditions is 35°C. The digestion temperature has a direct influence on the ultimate methane yield as well as the methane content of the biogas [9]. It has been shown that temperature has almost no effect on the ultimate methane yield of beef cattle manure for temperatures between 30 and 60°C [10]. The methane yields that are obtained at a temperature range of 15 – 20°C is about 26 – 42% of the yields achieved at 35°C [11]. The percentage of methane in biogas produced under thermophilic conditions (55°C) is on average 2% higher when compared with biogas produced under mesophilic conditions (35°C) [12], but the amount of energy used to heat the substrate to 55 °C is not economically warranted by the additional amount of biogas produced under thermophilic conditions. The shorter HRT of thermophilic temperatures when compared to mesophilic temperatures makes thermophilic temperatures more favourable but does not have an impact on the ultimate biogas yield and there is a risk of destroying the bacteria due to temperature fluctuations. Thermophilic bacteria (±1 °C) are more sensitive to temperature fluctuations than mesophilic bacteria (±3 °C). Mesophilic temperatures are therefore more favourable when it comes to economical biogas production because the mesophilic bacteria are more tolerant to temperature fluctuations, without significant reductions in methane production [1] .

2.4.2 pH level

The AD process is sensitive to pH level, thus changes in pH level can cause the inhibition of biogas production. pH levels that are too high or too low inhibit the growth of methanogenic microorganisms, which then reduces the production of biogas. Methane production occurs in the pH interval between 5.5 and 8.5. The optimum pH level for methanogens to form methane is between 6.7and 7.5 [2]. Cattle manure is suitable for AD to produce biogas as it has a pH level of 7.5 that is within the optimal range of pH [13]. The AD process is severely inhibited when the pH level decreases to below 6.5 (acidic) and rises above 8.5 (alkaline).

2.4.3 Mixing

Proper mixing is essential for optimal performance of a large-scale AD system and can have an effect on biogas production. The mixing of the digester sludge prevents the formation of surface scum layers and the deposition of solids on the bottom of the digester tank. The results from previous studies showed that mixing improves the process performance of AD, by increasing biogas yield. When compared to cases with continuous (control) mixing, Kaparaju et al [14] showed that intermittent (mixing for 2 hours prior to extraction/feeding the digester) and minimal (mixing for 10 minutes prior to extraction/feeding of digester) mixing strategies improved methane production by 1.3% and 12.5% respectively. The effect of mixing intensity in batch tests showed that when the process is overloaded by high substrate to inoculum ratio (40/60), gentle mixing (35 rpm) or minimal mixing (10 minute mixing before feeding) was advantageous compared to vigorous mixing (110 rpm). On the other hand, under low substrate to inoculum ratio (10/90), gentle mixing performed the best [14]. Thus mixing schemes and intensities have some effect on AD of manure. In laboratory scale biogas digesters it was observed that higher methane production rates were achieved in the unmixed digesters than in the continuously mixed digesters [15]. Thus, in lab scale tests mixing will have little to no effect due to the amount of digestate in the digester, but periodic shaking of the digester bottles is recommended to release gas bubbles. Large scale biogas digesters are mixed for practical reasons to stop surface scum layers forming and sediment formation at the bottom of the digester in Continuously Stirred Tank Reactor (CSTR).

2.4.4 Hydraulic retention time

The HRT is defined as the parameter for dimensioning the biogas digester; it is the average time interval that the substrate is kept inside the digester. The retention time must be long enough to ensure that the amount of microorganisms produced in the digester exceed the microorganisms removed in the digestate. A 25 day HRT is recommended for effective AD of organic matter under mesophilic conditions [16]. The shorter HRT provides good substrate flow, but delivers low biogas yields due to the microorganisms escaping in the digestate. In AD the methane production (ml methane per gram VS added) decreases as the HRT decreases

[17]. Siddique et al [18] found that at HRT's of 10, 7, 4, 2.5 and 1.5 days the methane production was 83, 76, 71, 69 and 63% of the maximum value respectively under mesophilic (37°C) AD. El-Mashad and Zhang [19] recommend an HRT of 20 days and found that about 90% of the final biogas can be produced when digesting dairy cow manure under mesophilic temperatures with this HRT.

2.4.5 Concentration of microorganisms

Methanogenic bacteria have a regeneration time of 10-16 days whereas the other microorganisms like hydrolytic (less than 2 hours), acidogenic (less than 24 hours) and acetogenic (less than 90 hours) bacteria have a regeneration time of hours [2]. When starting a biogas digester for AD it is required that the bacteria build up over a long period before the digester produces biogas at full capacity. Alternatively, the digester can be seeded with inoculating sludge from a healthy digester to speed up the AD process. Another source for seeding a biogas digester with inoculating microorganisms is rumen fluid which has an abundance of methanogenic bacteria (10^7-10^9 cells per ml) and other anaerobic bacteria to promote the AD process [2]. Cattle manure is exposed to ruminants in the cow's stomach which extract much of the nutrients from the fodder and the leftover is rich in lignin complexes which were extensively exposed to enzyme action of the four-chamber stomach of ruminants [20]. The lack of methanogenic bacteria typically leads to VFA accumulation and subsequent acidification of the digester, thus inhibiting methane production [6]. Budiyono et al [21] found that rumen fluid inoculums caused biogas production rate and efficiency to increase two to three times when compared to manure substrate without rumen fluid.

2.4.6 Volatile fatty acids

The VFA are produced during acidogenesis and are intermediate compounds (acetate, propionate, butyrate, and lactate) [1]. In most cases instability in the AD process is caused by the build-up of VFA inside the digester. This causes the pH level to drop thus destroying methanogenic bacteria that produce methane. Higher VFA levels have been observed to occur at thermophilic digestion temperatures rather than at mesophilic temperatures [10]. This increase of VFA causes a decrease in biogas production.

The accumulation of VFA makes the AD process unstable and inhibits bacterial growth for methanogenic activities. A steady AD process can be established with the digestion of manure which increases the buffering capacity and offers a nitrogen source for bacteriological synthesis. Siddique et al [18] found that the concentration of VFA decreased from 500 mg/l to 154 mg/l under mesophilic (37 °C) conditions and almost non-traceable levels for thermophilic (55 °C) conditions in the case of AD with cattle manure.

2.4.7 Ammonia concentration

Ammonia is mainly formed from proteins and has a significant function in the AD process. Too high ammonia concentrations inside the digester are responsible for the inhibition of the anaerobic bacteria especially methanogenic bacteria. The concentration of ammonia is directly proportional to increases in temperature. There is thus an increased risk of ammonia inhibition of the AD process operated at thermophilic temperatures, compared to mesophilic temperatures.

When the digester is inhibited by ammonia, an increase in VFA concentration will cause the pH level to drop and become more acidic [1]. A temperature decrease from thermophilic to mesophilic will have a positive result in the AD process because ammonia levels will drop. It was shown by Kaparaju et al [10] that decreasing the process temperature of digestion is a good option for overcoming ammonia inhibition in anaerobic digesters. However, decreasing the temperature increases the required retention time and the growth rate would be reduced.

2.4.8 Specific surface area of biomass

The surface area of the organic material must be as large as possible to speed up the AD process and to bring a large surface area of the biomass into contact with the anaerobic bacteria. The rate of degradation of biomass is increased by increasing the surface area. In the first few days the biogas generated from biomass with large surface area is much more vigorous than the biomass with a smaller surface area [2]. The enlargement of the organic material surface area positively impacts the microbiological hydrolyses and degradation process. One important aspect that needs to be considered is that the energy spent to enlarge the surface area of the organic material must be less than that gained by biogas production increase.

2.5 Cattle manure generation and characteristics

The large number of cattle in South Africa generates significant amounts of manure that can potentially produce biogas through the AD process. The biogas yield can be determined with a calculation based on the raw nutrient content within the substrate. The assumption is made that methane yields depends only on the content of digestible proteins, fats and carbohydrates [1].

Manure contains all sorts of unwanted inorganic matter like sand and small rocks which cannot be broken down by the anaerobic bacteria. The manure can also contain other unwanted matter like antibiotics and disinfectants that kill the anaerobic bacteria and are thus undesirable for anaerobic digestion and biogas production. The composition of cattle manure differs from animal to animal because each type of cattle (dairy cows, breeding cows and calves) has its own diet.

The freshly excreted cattle manure has a TS content of 25% to 30% and its VS can be as high as 80% (as a % of TS) [2], whereas aged cattle manure's VS depends on the time it has aged and the environmental conditions as it decomposes over time. The composition of manure is expected to change as the seasons change from winter to summer, thus the manure samples must be taken within the same season for analysis purposes [22].

2.6 The techno-economic basis for biogas plant design

The basic equipment of an agricultural biogas plant consists a preparation tank, biogas digester, digester heat exchanger pipes, pumps, biogas holder, biogas engine and residue storage tank. The Preparation tank is used to store the feedstock until it is fed into the biogas digester and is usually a cylindrical concrete tank. The biogas digester can be any shape but the most economical shape is a vertical cylindrical tank that is constructed from concrete. The biogas digester can be agitated with retractable agitators to break down the floating layers of the digester content. The heat exchanger consists of a network of thin pipes within the digester through which hot water is pumped and to heat the contents in the biogas digester. The biogas holder is usually a low pressure plastic membrane gas holder that is used to store the produced biogas and feeds the biogas engine as it requires biogas to generate electricity. The residue storage tank is used to store the digestate until it is sold as fertiliser and is usually a cylindrical tank constructed from concrete.

The economic viability of the construction of a biogas plant has high risks due to fluctuation in the economic environment. The lifespan of the biogas plant must be long enough to generate the return of the initial investment. The Net Present Value (NPV), IRR and the payback time period are economic tools to determine the economic viability of projects that require high investments. The NPV uses the time value of the money streams over time, but it does not provide a rate of profitability. Thus the IRR is the determining factor in determining the profitability of a project and weather the project would be economically viable, the higher the IRR the higher the economic profitability. Orive et al [23] conducted a sensitivity analysis that indicated that the electricity sale price was by far the most significant factor in the profitability variation of a biogas plant. The government should thus give higher incentives to electricity production from renewable sources such as biogas to make projects more attractive to investors.

The Return on Investment (ROI) is an indicator of economic attractiveness of a project in a simplified form. The ROI is defined as the percentage of the net annual income over the total investment costs. The following ROI values will deem a biogas project plausible or not [24]:

ROI < 8% - the project is unattractive to investors

8% < ROI < 13% - the project might be worth considering in more details

ROI > 13% - the project is attractive and will enter the economic potential.

The NPV is the potential change in wealth caused by the project investment when the time value of money is accounted for. The NPV equals the present value of net cash inflows generated by a project less the initial investment on the project. The following formula is used to calculate the NPV of a project investment [25] :

Equation 6

$$NPV = \left(\sum_{t=1}^{t=n} \frac{R_n}{(1+i)^n}\right) - Initial\ Investment$$

Where, R_n is the net cash inflow for the period n and i is the interest rate.

The IRR is the discount rate at which the NPV of the project investment becomes zero. The IRR is the discount rate which equates the present value of the future cash flows of an investment with the initial investment. The following formula is used to calculate the IRR of a project investment [25] :

Equation 7

$$\left(\sum_{t=1}^{t=n} \frac{R_n}{(1+IRR)^n}\right) - Initial\ Investment = 0$$

2.7 Conclusion

The AD process to generate biogas from organic biomass is carried out by hydrolysis, acidogenesis, acetogenesis and methanogenesis. These four process steps are highly sensitive to change in operational conditions which can kill the biogas forming bacteria. Cattle manure contains the necessary proteins, fats and carbohydrates that are required to produce biogas. The ROI, NPV and IRR are economical tools that are used to determine whether a project will be economically viable or not. Chapter 3 that follows will provide an overview of the investigations that were carried out by other researchers on the topic of AD to produce biogas.

CHAPTER 3: Literature study

3.1 Introduction

This chapter gives an overview on the results achieved by other researchers on the topic of biogas production from animal manure and other biomass sources. All the investigations done by others were aimed at optimising and improving the AD process to produce the maximum amount of methane. These researchers focused on different process parameters like temperature, mixing intensity, HRT and pH levels to improve the AD process. The impact of cattle manure aging, biogas digesters and associated methods, the effects of temperature, biogas yields from manure and the inoculation of biogas digesters is discussed in this chapter.

3.2 The impact of cattle manure storage and aging on biogas yield

The carbon to nitrogen ratio (C:N) is an important parameter in the production of biogas. The C:N ratio affects the biogas yield and the quality of the biogas. When manure is left on a stockpile or stored in a pit and exposed to air, the levels of carbon and nitrogen within the manure change. Atallah et al [26] found that by stockpiling cattle manure 17% carbon is lost and 25% nitrogen is gained when compared to fresh cattle manure over a period of three months. As a consequence of aging manure the C:N ratios decreased with increased storage time. They also found that there was a direct relationship between the biodegradability index values and the C:N ratio which has an effect on biogas production.

The disintegration of cattle manure by aging negatively affects the C:N ratio of cattle manure. The low C:N ratio is a substantial factor which might be the restraint in the AD process. Siddique et al [18] found that the maximum methane yield in their experiments occurred at a C:N ratio of 30:1 which satisfied the bacterial demand. The C:N ratio can be improved to optimum ratio for methanogenesis by co-digestion technology with a mixture of substrates [18].

3.3 Biogas Digesters and associated methods to produce biogas

A lab-scale biogas digester can be constructed to evaluate the biogas potential of a particular type of biomass. This lab-scale digester will predict the biogas yield for a larger scale biogas plant and allows the AD process to be studied. Wilkie et al [27] developed a low-cost biogas digester that is inexpensive and very reliable to predict the biogas potential of a specific substrate. The BMP test as described by Owen et al [28] and Chynoweth et al [5] provides a method to estimate the ultimate methane yield of a particular biomass.

The design size of a biogas digester is determined by the substrate concentration in terms of total suspended organic solids. The biogas production increases within a short period of time when the biogas digester is fed with low substrate concentration [29]. However, the low substrate concentration will increase the required size of the biogas digester and increase capital costs. It is therefore vital to consider the optimal substrate concentration and HRT to design economic biogas digesters.

In general biogas that is removed from the digester is replaced by new gas molecules formed in the slurry of the digester. Ukpai and Nnabuchi [30] carried out three different batch tests that revealed that the more the biogas was removed from the system the higher the production. Their study also revealed that cow manure was the more favourable substrate to use as biomass when compared to cowpea and cassava peelings. The cow manure had a lower required retention time and formed higher volumes of biogas than the other two.

The accumulated biogas produced is measured in terms of the volume of gas formed per mass of VS. The VS is broken up further into its chemical characteristics such as VFA, lipids, protein, lignin and carbohydrates which all contribute to the production of biogas. Moller et al [31] investigated the methane productivity of dairy cattle manure incubated at 35 °C. The samples were kept frozen until they were used in the batch experiment. They found that the dairy cattle manure had an ultimate methane yield of 148 l/kg.VS.

The VS is an important factor in determining the BMP of a particular type of biomass, as the VS is broken down to produce biogas. Triolo et al [32] developed an algorithm to predict the BMP and found that lignin concentration within the VS was the strongest predictor of BMP for animal manures. Their studies showed that the lignin fraction could be used to predict the BMP for a combined model for animal manures. The square of the sample correlation factor (R^2) from the BMP versus lignin was found to be 0.908 [32]. Amon et al [33] found that the manures with the higher CP levels gave higher methane yields during AD. The lignin and CP fractions are thus important characteristics to determine when analysing a particular biomass for AD.

The composition of the biomass as a fraction of the VS can be broken up into its basic components to evaluate the biomass for methane production. Angelidaki et al [34] developed a comprehensive model where the biomass is described by its composition of basic organic components like carbohydrates, lipids, proteins, VFA, ammonia, phosphate, cations and anions. These components are then used in a mathematical model that simulates co-digestion of different wastes to predict the process behaviour and the outcomes of the BMP test. The mathematical model was verified with lab-scale CSTR digesters fed with cattle manure at 55 °C with HRT of 15 days. This model can be used as a tool to assist in the operation of full-scale biogas plants for process behaviour but only at 55 °C.

The methane production in the BMP test can be improved by the pre-treatment of the biomass. This pre-treatment can significantly improve the methane production. Carrere et al [35] investigated the impact of thermo-alkaline pre-treatment and found that the methane production increased by 58% when the substrate was pre-treated with potassium hydroxide at

80 °C, although the treatment was found to be not economical. Their tests showed an enhancement in the AD rate but a very low impact on the BMP results in terms of accumulated biogas.

Another method of improving the process performance of AD and increasing methane production is to co-digest different types of biomass. Marañón et al [36] found that 603 l/kg.VS methane can be obtained by co-digesting 70% dairy cattle manure, 20% food waste and 10% sewage sludge. The experiment was carried out using a CSRT operating at 36 °C with a 22 day HRT. They also found that increasing the temperature to 55 °C increased the rate of biogas production but lowered the total methane yield.

3.4 The effects of temperature on anaerobic digestion and biogas production

AD of animal manure can be initiated at temperatures as low as 5°C in batch scale digesters, provided the digesters are seeded with inoculum [37], but the bacteria require higher temperatures to survive and reproduce. The inoculum introduces the anaerobic bacteria required for AD. The production of methane gas is not possible without inoculum at temperatures below 20°C. It was shown by Zeeman et al [37] that under psychrophilic and mesophilic digestion temperatures an inoculum must be added to initiate and speed up the process of AD.

The temperature at which AD takes place has a direct influence on the ultimate methane yield as well as the methane and carbon dioxide content of the biogas. Chae et al [9] investigated the effect of temperature shock under mesophilic conditions (25, 30 and 35°C) and found that the methane content increased with an increase in temperature, but only to a small degree. A 3% drop in methane yield was observed as the temperature was decreased from 35 to 30° and a 17% drop when the temperature was decreased from 35 to 25°. They also found that temperature shocks from 35 to 30°C and again from 30 to 32°C led to a decrease in biogas production rate, but that the accumulated volume biogas was the same as the control digester. The temperature only changed the rate at which biogas was produced and not the accumulated volume. This leads to the conclusion that methanogens are quite sensitive to temperature changes but they have the ability to adapt to temperature changes. The ultimate methane yield is influenced by temperature in such a way that it affects the rate of fermentation. Hashimoto et al [38] showed that the methane production rate for a digester operating at 45 °C is higher than for one operating at 35 °C, but that there is little to no apparent difference in the total methane yield over a long period of time (163 days). They also concluded that temperature affects the rate at which methane is produced but does not increase the amount of methane that can be produced from a unit mass of cattle manure. The factors that affect methane yield are the age of the manure and the degree of contamination with inorganics (i.e. sand) [38].

Otero et al [39] observed a greater gas volume production under mesophilic (35 °C) conditions than under thermophilic (55 °C) conditions, but the thermophilic temperature presented a higher rate. They also reported that there is a reduction in methane yield with an increase in temperature from mesophilic to thermophilic. Their findings also showed that the maximum methane rate under mesophilic and thermophilic conditions was obtained at day 30 and day 10 respectively. Mesophilic temperatures present higher methane yields in AD in accordance with the lower value of activation energy required and thus indicate a higher conversion of organic matter than thermophilic temperatures [39].

Biogas digesters operated under thermophilic (55°C) temperatures can sustain higher organic loading rates, operate at shorter HRT and generate biogas at faster rate when compared to mesophilic (37°C) temperatures [18], but the shorter HRT gives less time for the methanogenic bacteria to react on the biomass and produce less methane gas. Siddique et al [18] showed that the methane percentage of the biogas increased to 31%, 40%, 45% and 67% at HRT's of 2, 4, 7 and 10 days. Their results showed that thermophilic temperatures produced more biogas than mesophilic temperatures, but only to a small degree. It is thus more economical to operate a biogas digester under mesophilic temperatures due to the cost of heating the digester to thermophilic temperatures when taking into account the amount of biogas produced and comparing it to the heat input to the process.

3.5 The kinetics of biogas production

The kinetics of biogas production plays an important role in the AD process in terms of the rate of biogas production and the cumulative biogas formation. The kinetics of biogas production rate was studied by Budiyono et al [21] where a model was developed for the biogas production kinetics in batch mode. The model made use of the Gompertz equation [21] to predict the biogas production rate for cattle manure in batch mode:

Equation 8

$$P = A.\exp\{-\exp\left[\frac{Ue}{A}(\lambda - t) + 1\right]\}$$

Where P (ml/g.VS) is the cumulative of specific biogas production; A (ml) is biogas production potential; U (ml/g.VS.day) is maximum biogas production rate; λ (days) is the lag phase period (minimum time to produce biogas); and t (days) the cumulative time for biogas production. Their model simulated and compared the influence of rumen fluid on cumulative biogas production as well as the influence of temperature to kinetic constants. In both cases the liquid rumen seeded to the biogas digester had a significant effect on the cumulative biogas production and the biogas production rate.

A comparative kinetic study on the AD of cow manure was carried out by Borja et al [40], in which bioreactors were supported with zeolite and suspended biomass. Their experiments were characterised kinetically to facilitate comparison between the experimental work and their model, their experimental work coincided with their predictions of their model. They used the following equation to develop a first order kinetic model to describe the accumulate methane volume G (l) at a given time t (days) [40]:

Equation 9

$$G = G_m[1 - \exp(-K_o t)]$$

Where G_m (l) is the maximum volume accumulated at an infinite digestion time and is the product of the initial substrate concentration and the yield coefficient of methane; K_o (days^{-1}) is an apparent kinetic constant that includes the biomass concentration in the digester. Taking the logarithms and reordering the terms, the following was obtained [40]:

Equation 10

$$\ln\left[\frac{G_m}{G_m - G}\right] = K_o t$$

This gave them an indication that $\ln[G_m/(G_m - G)$ versus t should give a straight line of the slope equal to K_o with intercept zero. Their model was qualitatively checked with experimental data and the parameter K_o was analytically calculated using a nonlinear regression program. Their model produced K_o values with 95 % confidence limits for each digester and experiment. The ratio between the kinetic parameters of the zeolite digester and control digester increased gradually with the substrate concentration to a maximum of twelve times for the maximum substrate concentration studied [40]. Their experimental work showed that the combined effect of ionic exchange and biofilm fixing significantly improved the kinetic constants, mean rate of methane production and yield coefficient of zeolite-supported digester in comparison with the control digester.

Yusuf et al [20] developed a modified Gompertz equation to adequately describe the cumulative biogas production from digesters at ambient temperatures (28-33 °C). The Gompertz equation was modified and reduced to:

Equation 11

$$\frac{1}{t}\ln\left(\frac{dyt}{dt}\right) = \frac{1}{t}(\ln ym + \ln k) - k$$

Where yt (ml/kg.VS) is the volume of biogas produced per unit mass VS fed at any time (t); ym is the volume of biogas per unit mass of VS converted at maximum time; k (days^{-1}) is the rate constant associated with the degradation of the biodegradability fraction; and t (days) is the period of digestion. Their equation was analogous to the straight line equation $y = mx + c$, in which the slope is represented by $(\ln ym + \ln k)$ and the $(-k)$ term represents the intercept of the plot against the inverse of the retention time. Their model fit the data set with a goodness of fit (R^2) of 0.9608. It was thus concluded that the short term room temperature kinetic of biogas production from cow dung can be effectively studied using the modified Gompertz model [20].

A first order kinetic model was developed by Chowdhury and Fulford [41], to predict the behaviour of both batch and semi-continuous AD systems. Their kinetic model defined constants which could be used to evaluate both systems. The daily gas production data from the batch system suggested that two rate constants were required to explain them: a higher rate at shorter retention times and a lower rate for longer retention times. They developed the following first order model for batch AD of cattle manure [41]:

Equation 12

$$\ln\left(1 - \frac{G}{C \times S_{do}}\right) = -k.t + k.t_o$$

Where G (m^3m^{-3}) is the cumulative specific gas production; C (m^3/kg) is the yield constant (the volume of biogas produced per unit mass of digestible feedstock destroyed); S_{do} is the concentration of digestible feedstock $S_{do} = S_o.f$, where S_o is the substrate concentration at time t = t_o and f is the digestible fraction in the total mass of the feedstock; and k ($days^{-1}$) is the rate constant. These models can be used to predict the gas production from full-scale digesters run in similar ways with similar feedstock at the same temperature [41].

3.6 Biogas yields from manure according to other researchers

The ultimate methane yield of beef cattle manure and dairy cattle manure is given in Table 3 for mesophilic and thermophilic temperatures as it was found by previous researchers. The table also provides the HRT and fermentation time for each specific experiment. Batch experiments of the BMP do not have a HRT as the digester is loaded with a defined amount of manure only at the beginning of the experiment and monitored until there is no measurable incremental amount of methane formation.

The methane yields range from 124 to 336 Nml/g.VS for mesophilic temperatures and from 136 to 316 Nml/g.VS for thermophilic temperatures. These manures were all gathered from different farms and the characteristics of each manure type differs in terms of TS and VS. The different farms provide their cattle with different diets, which leads to a variation in manure in terms of the VS.

There are other factors that contribute to the difference in methane yield as found by previous researchers. Each researcher investigated a specific process parameter of AD to produce methane. These process parameters include organic loading rates, HRT, pH levels, mixing intensities, screening of manure, pre-treatment of manure, inoculation source, liquid-solid separation and the type of digester used.

Table 3: Ultimate biogas yield of beef cattle and dairy cow manure from literature

Substrate	Operating temperature (°C)	Biogas yield (N ml/g.VS)	HRT (days)	Fermentation Time (days)	Reference
Beef cattle manure	38	172	Batch	60	[21]
Beef cattle manure	35	336	Batch	163	[38]
Beef cattle manure	55	316	Batch	163	[38]
Beef cattle manure	55	300	15	240	[10]
Dairy cattle manure	35	330	Batch	50	[37]
Dairy cow manure	55	246	15	69	[14]
Dairy cow manure	35	183	5	60	[42]
Dairy cow manure	35	255	9-12	180	[42]
Dairy cow manure	35	314	15-20	120	[42]
Beef cattle manure	35	193	Batch	75	[29]
Dairy cow manure	35	240	6	N/A	[17]
Dairy cow manure	35	260	8	N/A	[17]
Dairy cow manure	35	270	10	N/A	[17]
Dairy cow manure	35	307	Batch	45	[43]
Dairy cow manure	38	166	Batch	60	[33]
Dairy cow manure	35	148	Batch	100	[31]
Beef cattle manure	37	197	Batch	90	[32]
Beef cattle manure	37	124	Batch	90	[32]
Dairy cow manure	35	183	Batch	22	[44]
Dairy cow manure	35	241	Batch	30	[19]
Beef cattle manure	37	138	30	90	[45]
Beef cattle manure	55	136	30	90	[45]

N/A Stands for not available; Batch = batch tests of the BMP thus no HRT

3.7 Inoculation of biogas digester

The AD process is a slow and time consuming process that can be sped up by the addition of anaerobic bacteria in the form of inoculum. Siddique et al [18] showed that the AD process speeds up when using beef and dairy cattle manure as inoculum (because of the rumen and bacteria content) under mesophilic (37°C) and thermophilic (55°C) conditions in co-digestion with other substrates. They found that the methane yield and HRT of the overall process is improved by the use of inoculum in the AD process. However, they also concluded that the shorter HRT reduces the interaction time between substrate and bacteria which affects methane production. The performance of a biogas digester in terms of methane production depends on the HRT and the VS loading rate. Dugba et al [46] recommended that the VS loading rate be kept between 2 and 4 g/l/day when the system is operated with a low HRT of 3 days. They also showed that the use of inoculation to seed the digester in the form of municipal sewage waste water speeds up the process of AD. The use of an inoculant in a biogas digester has an influence on the HRT and the VS loading rate as there are more bacteria available to convert the VS into biogas.

At low psychrophilic temperatures (<20 °C) the anaerobic bacteria become inactive and stop producing biogas. A means of initiating the AD process under psychrophilic temperatures is to add inoculum to initiate the process of AD. Zeeman et al [37] showed that it is not possible to start up any type of psychrophilic digester at temperatures of 15 °C or lower without seeding the digester with inoculum. They also showed that it is possible to start a biogas digester at temperatures as low as 5 °C when using an inoculum. Their work showed that the start-up of an AD is possible at 20 °C or higher without inoculation, but that the fermentation time would be much longer than when an inoculum is added. The sources of inoculation used was sewage sludge, swamp oil, concentrated peat bog and fresh cattle manure [37].

The amount of inoculum added to a biogas digester is crucial for the performance of the AD process on start-up of the digester. Dechrugsa et al [6] suggested that the inoculant to substrate ratio should be higher than 3 (based on dry VS) to gain consistent results in the BMP test of solid substrates (in co-digestion of para grass and pig manure) in batch testing. They also found that although the inoculum from a digester treating a specific substrate may have superior methanogenic activity, it may not be suitable for use in the BMP test of a mixture of solid substrates. The dominant species of fermentative bacteria could be tested and be used as an indication of the fitness of the inoculum for the BMP test [6].

3.8 Techno-economic feasibility of biogas plants

The economic feasibility of a biogas plants is directly related to the sale of heat and electricity. The price of electricity from renewable energy such as biogas is predetermined by the utility, in this case the SA government through the state-owned company Eskom, and is the feed in tariff that is paid for the sale of electrical power produced from renewable energy sources. There are other factors that contribute to the feasibility of a biogas plant such as cost of feedstock, transportation of feedstock, disposal of waste cost, labour cost, operational and maintenance cost. Additional revenue for a biogas plant may be generated by selling the digestate as fertiliser and selling heat energy to the neighbouring community. Biogas as an alternative energy source must be environmentally beneficial and economically competitive in order to attract investors.

Li et al [47] showed through economic analysis of a full-scale biogas plant that it was not attractive as a commercial investment. They concluded that renewable energy production is not economically viable on its own, without considering the waste treatment function and the associated incomes for example, reduction of carbon dioxide emissions. There are other positive factors of a biogas plant that can potentially attract investors such as:

- disposal of waste that could cause drastic environmental damage
- waste treatment
- the positive impact of renewable energy on climate change and
- nutrient-rich fertiliser with reduced odour.

Orive et al [23] showed though economic analysis that the current market prices of electrical energy and organic fertiliser make the investment of a biogas plant unprofitable. They concluded that only in a framework with higher governmental incentives to electricity production from renewable sources and more stable fossil fuels and fertiliser sale prices a biogas plant becomes more feasible and attractive to potential investors. The biogas technology is evolving as a renewable energy source due to the fact that energy can be produced with environmental benefits.

The production of biogas requires heat use from biogas cogeneration plants to make the biogas plant economically viable. The actual heat usage of a biogas plant is location-specific as it could be used either for new demand (e.g. digestate drying) or replacing existing demand (e.g. greenhouse heating), which make the biogas plant economical attractive. Kulisic et al [24] suggests that if at least half of the heat is used to replace the existing demand, it would increase the economic potential of the biogas plant and make it attractive to potential investors. Table 4 indicates the techno-economic viability of biogas plants as obtained from literature.

Table 4: Techno-economic viability of biogas plants from literature

Feedstock	Plant size (kWe)	Capital investment (per year)	Operational Costs (per year)	Income (per year)	Pay back (years)	NPV	IRR (%)	Ref.
Pig slurry	62	€ 629 000	€ 142 665	€ 68 268	9.2	€ 135 701	11.3	[23]
Pig-olive slurry	262	€ 1 165 726	€ 144 250	€ 218 088	6.7	€ 782 493	13.7	[23]
Rice-wine-pig	108	$ 555 387	$ 9 755	$ 50 811	10.9	$ 10 000	6.0	[47]
Chicken-olive waste	100	€ 742 500	€ 58 472	€ 116 192	8.0	€ 430 103	-	[48]
Chicken-olive waste	300	€ 2 033 200	€ 149 954	€ 376 554	7.0	€ 1 726 789	-	[48]
Sewage	330	$ 4 723 276	$ 47 705	$ 663 849	7.0	$ 1 926 192	29.0	[49]
Cow/sheep dung	278	€ 10 262 109	€ 373 318	$ 336 936	30.0	€ 9 881 057	-	[50]
Abattoir	280	R15 860 740	R 554 753	R1926156	8.2	R 3 100 000	26.5	[51]

3.9 Conclusion

As a consequence of aging manure the C:N ratio decreases with increase in storage time which affects the biogas production. A means to determine the biogas potential is through a lab scale biogas digester. The BMP test is a method that is used to estimate the ultimate methane yield of a particular biomass. The VS is an important factor in determining the BMP of a particular type of biomass, as the VS is broken down to produce biogas. The process of AD can be perfected for individual applications in terms of operational temperature, pH levels, mixing intensity, inoculation and HRT.

The temperature at which AD takes place has a direct influence on the ultimate methane yield as well as the methane and carbon dioxide content of the biogas. The ultimate methane yield is influenced by temperature in such a way that it affects the rate of fermentation. The methane yields of manure can range from 124 to 336 Nml/g.VS for mesophilic temperatures and from 136 to 316 Nml/g.VS for thermophilic temperatures. The AD process can be sped up by using an inoculation source to promote the growth of anaerobic bacteria and reduce the HRT. However, the short HRT can reduce the interaction between substrate and bacteria which affects methane production. The performance of a biogas digester in terms of methane production depends on the HRT and the VS loading rate. The use of an inoculant in a biogas digester has an influence on the HRT and the VS loading rate because there are more bacteria available to convert the VS into biogas.

The literature study indicates that there is room for researchers to follow up on the work done by others and to optimise the AD process. These research areas include temperature variations, pH levels, HRT, inoculum source and co-digestion. The aging process, type of digester, temperature and inoculation are some of the parameters that have been researched to optimise the AD process. The research investigations from other investigators showed that a biogas plant can be economically viable from the sales of heat and electrical power and the sales of digestate as fertiliser. In chapter 4 the methodology of the manure sampling, manure aging and the BMP test is described as a method to indicate the biogas potential of manure.

CHAPTER 4: Methodology

4.1 Introduction

The present investigation will focus on the biogas yield from cattle manure ranging from fresh manure to aged manure. Small containers were used to mimic the behaviour of manure in a storage pit. The drying process of cattle manure was investigated for weight loss and the thickness of the dry layer of manure formed over time. The BMP test as described by Owen et al [28] was performed in batch form on samples of manure ranging from fresh manure to aged manure to investigate the effect that aging of manure has on biogas production.

The manure was aged for different time periods and immediately frozen until it was used in the BMP test. The manure was kept frozen to preserve the sample and to stop microscopic bacterial activities within the manure. The BMP test was performed on all the frozen manure samples using the same inoculation and operational conditions, this would cancel out discrepancies between the differently aged manure samples. Manure samples that were aged but not frozen were analysed in the BMP test to analyse the difference in biogas yield between frozen manure samples and unfrozen manure samples. A comparison can thus be made to see what effect the freezing process had on the biogas yield.

This chapter describes the method that was used to collect and analyse the cattle manure samples. Attention is given to the manure collection and sample preparation method used for aging the manure to simulate the degradation of manure in a storage pit where it is exposed to the environment. The aim was to simulate manure storage pits that are 50, 100, 150, 200 and 250 mm in depth. The methods of determining the TS, VS and CP as well as the drying front analysis of the manure is provided in this chapter. The manure then goes through an AD process as described in the BMP test to produce biogas. The biogas volume is adjusted to standard temperature (273.15 K) and pressure (101.325 kPa) and analysed with a GC (Gas Chromatograph) to analyse the biogas for methane and carbon dioxide content.

The same manure sample was divided into different containers (with constant height – aging test) to be aged to 4, 7, 11, 14, 21, 28, 35 and 40 days respectively and the individual samples were analysed in the BMP test. In a separate test (different heights – drying test) the containers had a stack height of 50, 100, 150, 200 and 250 mm respectively and were analysed for weight loss and manure top dry layer formation over a period of 40 days. The weather conditions were monitored for the period that the manure was drying in the open air exposed to the ambient conditions and direct sunlight on a concrete roof.

The manure samples were aged to the specified time and then kept frozen until they were used in the BMP test. The different manure samples in terms of age, frozen and not frozen were analysed for TS, VS and CP content. The manure samples that were analysed in the BMP test include fresh manure that was not frozen as well as fresh manure that was frozen. The frozen manure samples include 4, 7, 11, 14, 21, 28, 35 and 40 day aged manure respectively. Another sample that was aged to 40 days and not frozen was also analysed in the BMP test.

A total of eleven manure samples were thus analysed in the BMP test for biogas volume formation as a function of time. The biogas of each manure sample was analysed once a week for methane and carbon dioxide content depending on the amount of gas produced. The rumen that was used to seed the digesters with anaerobic bacteria was also analysed for biogas volume, methane and carbon dioxide content. Three different rumen samples were used as inoculant: one for fresh manure not frozen, one for all frozen manure samples and one for the 40 day aged manure that was not frozen.

4.2 Manure sampling and analysis procedure

The manure sampling was done as described by Kissinger et al [52]. The cattle manure samples were collected at Kameeldrift feedlot near Cullinan. The feedlot has between 7000 and 8000 beef cattle at any time. The manure samples were collected in the stalls early in the morning to ensure that the manure was as fresh as possible. The method that follows was implemented to sample and analyse the manure.

Different subsamples were taken at random locations in the stalls to make up a good sample of fresh manure. The subsamples were mixed thoroughly in a large container (30 L) to achieve a homogeneous manure sample. The homogenised sample of manure was then divided into subsamples and placed in transparent cylindrical sampling containers of different height but with the same diameter of 90 mm. The drying characteristics of the manure were tested using containers of varying heights, while BMP testing was done on manure samples dried for varying times in containers of uniform height (150 mm).

For the drying test, the sampling containers had stack heights of 50 mm, 100 mm, 150 mm(x16), 200 mm and 250 mm respectively and were exposed to the environment (20 containers). The corresponding volumes of the 50, 100, 150, 200 and 250 mm containers were 320, 640, 950, 1270, and 1590 ml respectively. Each sampling container was filled to the top with manure and had an accuracy of 5 mm with respect to the top end of the container. Each container was labelled to distinguish between the different ages of the manure (150 mm height). The samples where covered with a net to prevent insects from contaminating the samples and left to age in the open air.

One sample was placed in a freezer (at -18 ^{0}C) prior to drying to act as a control for fresh manure. Freezing will preserve the composition of the manure and stop micro-bacterial activities within the manure for accurate analysis of the manure in the BMP assay [18]. The fresh manure sample was analysed for TS, VS and CP and the BMP test was performed on the fresh unfrozen manure sample. There were sixteen containers with a 150 mm heights since these were used to investigate the influence of the aging time of the manure on biogas formation.

Each container was weighed before the drying process started to determine the initial mass of the container and any reduction in weight was assumed to be water loss together with bacterial activities converting biomass to gas. It was observed that there was some bacterial action during drying resulting in conversion of biomass to biogas. After one week two 150 mm containers were removed and placed in the freezer, one for each duplicate BMP test. This would simulate a manure sample that was aged for one week. One of the two samples aged for one week was analysed for TS, VS and CP while the other one was analysed in the BMP test for biogas generation.

Each sample was weighed before it was placed in the freezer to determine the weight loss of the manure sample for that period. The thickness of the dried manure layer at the top of the containers was then measured with a Vernier calliper through the transparent container wall. This dry layer of manure separates the wet manure on the inside of the container from the environment.

At varying times (see below) two additional 150mm containers were placed in the freezer until all sixteen containers were in the freezer (40 days). These were subsequently analysed using the BMP test. The containers with varying heights (50 mm, 100 mm, 200 mm and 250 mm) where used for the drying analysis and weight loss at different heights. The weather data was retrieved from the University of Pretoria weather station for the drying period and includes the half hourly air temperature, relative humidity, wind speed, rainfall and barometric pressure. The samples were aged in close proximity to the weather station.

The night before the start of the BMP test all the frozen samples were left to defrost at room temperature. Each sample was then diluted with distilled water to obtain a liquid mixture with a calculated TS concentration of 7%. Eleven samples of manure from the same batch were subjected to the BMP test, but each was treated differently: eight samples (each originally 150mm in thickness) were aged for 4, 7, 11, 14, 21, 28, 35 and 40 days respectively and then frozen, two fresh manure samples (one that was frozen and one that was not frozen), and a sample aged for 40 days but was not frozen.

4.3 Manure sample drying front analysis

The manure drying process was conducted during the winter months of South Africa (June – August) to avoid rain contaminating the samples. The samples were left to dry in the open air and were exposed to direct sunlight and wind. During this period, no rainfall was recorded by the weather station.

The top dried layer thickness was measured with a Vernier calliper and a photograph was taken to confirm the thickness of the top dry layer of manure. Measurement of the drying front thickness and weight loss was done on a weekly basis.

Over time the thickness of the dry top layer of manure would increase and form a manure "lid" that separates the wet manure from the outside air. This dry manure "lid" would then act as a porous media through which water vapour can escape. While the manure is in the container it undergoes some fermentation as the manure is decomposing anaerobically on a microscopic level and this would also account for some of the weight loss of the containers. The outside ambient temperature was hot enough to heat the containers to favourable AD temperatures as it was exposed to direct sunlight. The manure inside the container would dry out completely if it is left long enough over a period of months.

4.4 Methods for determining TS, VS and CP (nitrogen) of manure according to AOAC, 2000.

The manure analysis was carried out in a laboratory at the University of Pretoria under controlled conditions. The TS, VS and CP of the manure was determined in a laboratory under controlled environmental conditions. The TS percentage was determined by drying each sample in an oven at 135 ±2 °C until there was no further weight loss in the sample, thus until all the water has evaporated according to the AOAC Official Method 930.15 [53]. The VS percentage was determined by putting the dried sample in a temperature controlled furnace preheated to 600°C. This will burn off all organic compounds (VS) and the remaining ash contains all inorganic compounds. The VS is thus the total dry sample weight less the ash weight, according to the AOAC Official Method 942.05 [53].

The CP (nitrogen) content of the manure was determined using the Dumas method, according to the AOAC Official Method 968.06 [53]. The dried sample was ground to pass through a No. 30 sieve and stored in capped bottles. The nitrogen was measured with a suitable instrument (Coleman model 29A nitrogen analyser) that combusts at 850 °C – 900 °C. Nitrogen freed by pyrolysis and subsequent combustion, is swept by carbon dioxide carrier gas into a nitro-meter. Carbon dioxide is absorbed in potassium hydroxide and volume residual nitrogen is measured and converted to equivalent protein by a numerical factor of 6.25. The biogas that was obtained from a sample was expressed as the amount of biogas per gram of VS within the manure sample.

4.5 Experimental setup and procedure – The BMP test

The experiments were conducted according to the specifications of the BMP test as described by Owen et al [28], Hansen et al [54] and Esposito et al [55]. The BMP test is a procedure developed to determine the ultimate biogas yield of an organic material during its anaerobic decomposition by a mixed microbial flora in a defined medium. The BMP test provides a direct means to predict and monitor relative biodegradability of substrates and the biogas yield.

The gas chromatography was done in a laboratory at the University of Pretoria. The 150 mm (9 frozen samples) stack height manure samples, fresh manure sample (not frozen) and one sample aged to 40 days (not frozen) was analysed in the BMP test (11 different samples). The following steps describe the method that was used to determine the biogas yields of all the samples.

1. Each sample was tested in duplicate under the same conditions to get a good average of the biogas formed.
2. Each sample was diluted with 500 ml (fresh manure) to 620 ml (manure aged to 6 weeks) distilled water depending on the weight loss during the aging process to achieve a liquid mixture based on a weight concentration. The amount of water added was determined by the weight loss for each sample and a calculation was done to achieve a diluted TS concentration of 7 %.
3. Each sample was mixed thoroughly with a stick blender (Safeway, 200 W) to ensure that it was fine enough to have a large enough surface area for the bacteria to react on, thus no big lumps.
4. An 800 ml liquid sample (diluted to 7% TS concentration) was poured into a 1000 ml Duran GL45 laboratory glass bottle.
5. 50 ml of inoculant (rumen fluid) was added to ensure that the anaerobic digestion process was initiated. The rumen fluid was collected from an experimental dairy farm at the University of Pretoria.
6. 20 ml sodium hydroxide with a concentration of 2% (2 gram sodium hydroxide per 100 ml of water) was added to get a base pH between 7 and 8 [27]. The pH of each sample was measured with litmus paper before starting with the BMP test and after the BMP test.
7. A control sample containing only 50 ml of inoculant and 800 ml distilled water was prepared. This will simulate the amount of gas formed by the inoculant without the manure.
8. Each reactor bottle was flushed with nitrogen gas to remove oxygen from the reactor bottles and ensuring anaerobic fermentation conditions.
9. The reactor bottles were closed with an air tight sealing lid (Duran GL45 screw cap with 2 hose connectors) to ensure anaerobic conditions. The lid contains two exit ports, one used to measure gas volume and another used to draw a sample to analyse the gas for methane and carbon dioxide content.

10. The reactor bottles were placed in a temperature controlled water bath at 35 ±1°C, the temperature was kept constant with a 300 W water heater and a circulating pump.
11. The reactor bottles were shaken gently daily to promote the release of biogas and to mix the sample.
12. The reactor bottles were connected to a manometer type gas measuring tube (See figure 45 in the appendix) every day and the daily biogas formation was measured, until there was no visible gas formation after 40 days of AD.
13. Measurements were taken of:
    - The volume of gas formed in each reactor vessel (daily).
    - The ambient temperature and pressure (daily).
    - The methane and carbon dioxide content (twice a week).
    - The pH of each reactor vessel (before and after the BMP test).
    - The weight of each reactor vessel (before and after the BMP test).
14. The daily and cumulative biogas production of each sample was compared as well as the methane and carbon dioxide content.
15. The biogas evolution was determined as a function of time to determine the optimum design point for biogas digester designers. This is the time required for the manure to produce 80% of its maximum biogas production [8].

The experimental setup consisted of 28 digester bottles, i e 14 samples tested in duplicate. These samples include 11 differently treated manure samples as well as 3 different rumen samples. Figure 3 is a schematic diagram of the experimental setup and shows the biogas digester bottle, temperature controlled water bath and the detachable manometer used to measure the biogas volume.

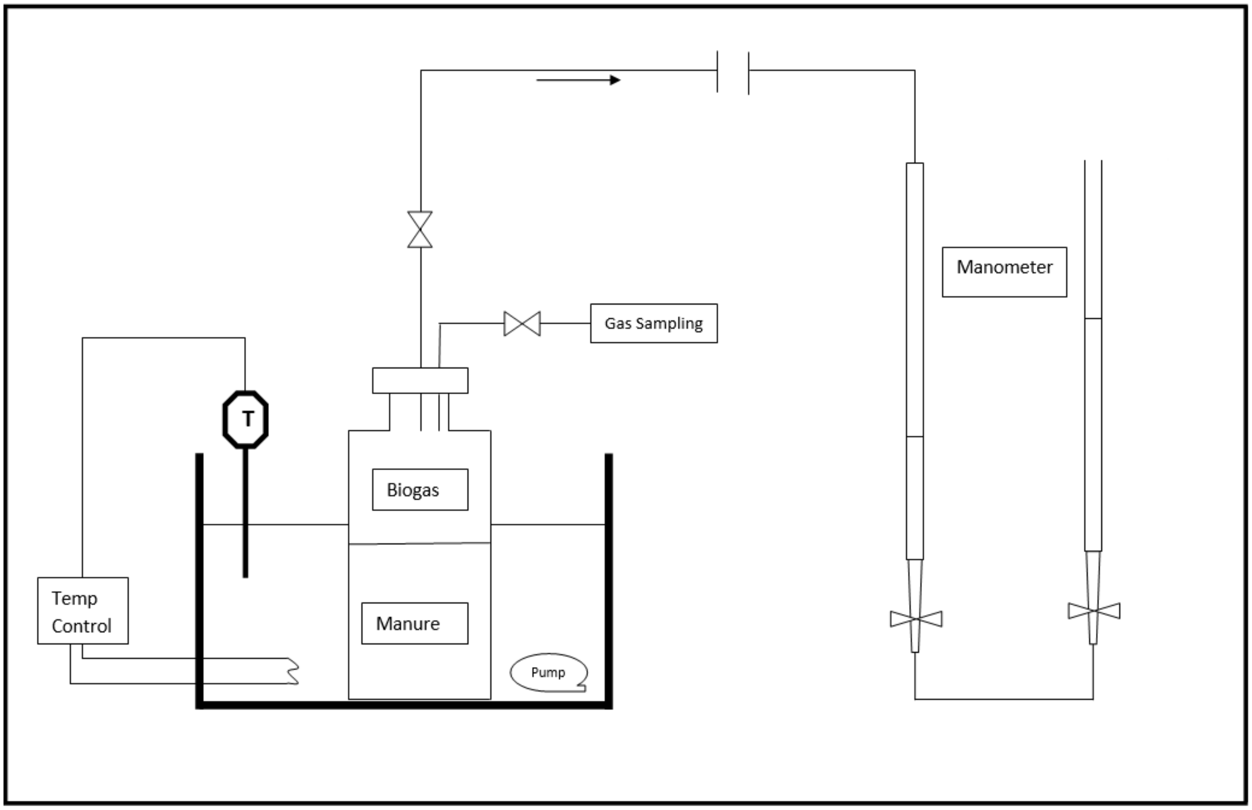

Figure 3: Diagram of experimental setup

4.6 Biogas analysis for methane and carbon dioxide content

Twice a weak each biogas sample was analysed for methane and carbon dioxide content. The biogas was collected in 60 ml syringes and analysed on the same day it was extracted from the reactor bottles. Each gas sample was analysed twice to get an average analysis of the methane and carbon dioxide content.

An SRI 8610C gas chromatograph with FID & ECD detector was used. Nitrogen was used as a carrier gas through the Haysep D column. The GC was calibrated using standard methane gasses of 100, 300 and 10 000 ppm respectively and with 500 ppm carbon dioxide gas. 2 ml biogas was injected manually into the GC with a valve controlled syringe into a 1 ml loop. The GC analysed the gas sample and used a program called PeakSimple to quantify the methane and carbon dioxide content within the sample of biogas.

4.7 Conclusion

This investigation was aimed at analysing the biogas yield from different samples of cattle manure ranging from fresh manure to aged manure. The manure samples were aged to 4, 7, 11, 14, 21, 28, 35 and 40 days respectively and kept frozen until used in the BMP test. Fresh manure that was not frozen, fresh manure that was frozen as well as manure that was aged to 40 days and not frozen was also analysed in the BMP test. The VS, TS and CP of each manure sample was analysed in a laboratory according to standard methods. The biogas digesters were all seeded with rumen fluid to speed up the AD process. The biogas production was measured daily and a comparison was made between the biogas yield from fresh manure and aged manure. The percentage methane and carbon dioxide in the biogas was measured twice a week with a GC to monitor the percentage variations of the different samples of biogas over time. The pH level of each digester was measured before and after the BMP test to monitor changes in pH levels before and after the BMP test. The biogas evolution as a function of time of each sample of manure was compared to each other. In Chapter 5 the results of the BMP are presented and the data is interpreted.

CHAPTER 5: Presentation and interpretation of data

5.1 Introduction

The findings of this research are given in this chapter, which presents and interprets the obtained data. The manure samples were analysed for the formation of the top dry layer formation as well as for weight loss. The moisture within the manure sample reduced and the top dry layer of manure became thicker over time. The ambient weather conditions have a direct effect on the moisture loss and the drying process. Weather data was therefore collected for the specific period that the manure was left to dry. Each manure sample was analysed for nutritional value in terms of TS, VS and CP.

The manure samples were then analysed in the BMP test for biogas formation over a 41 day period. The rumen samples were also tested separately to measure the biogas produced from the rumen. The accumulated biogas volumes that were produced was in line with the values obtained by other researchers in the literature study. The quality of the biogas samples was determined in terms of the methane and carbon dioxide content. The average accumulated methane and carbon dioxide percentages obtained were also within the expected ranges for biogas as given by the literature.

5.2 Manure drying front and weight loss

The containers were filled to the top with fresh manure and monitored for the thickness of the top dry layer of manure formation and weight loss over a 40 day period. The manure dried inward towards the centre of the container as water evaporated. During the drying period small gas pockets formed in the wet part of the manure (see figures 40 to 42 in the appendix). This was a clear indication that there was some gas formation within the wet part of the manure while the manure was aging. This confirmed that some of the biomass was converted into gas during the drying process.

Figure 4 shows the thickness of the dry layer as a function of time for each container depth tested. The dry top layer of manure formed a “lid”. The 50 mm high container was completely dried out after 14 days due to the fact that the mass stayed constant thereafter. The 100, 150, 200 and 250 mm containers still had moisture contained within the manure and showed a constant rate of weight loss. This was an indication that it was not the dry layer of manure that presented the barrier to evaporation, but the rate at which water was released by the wet manure.

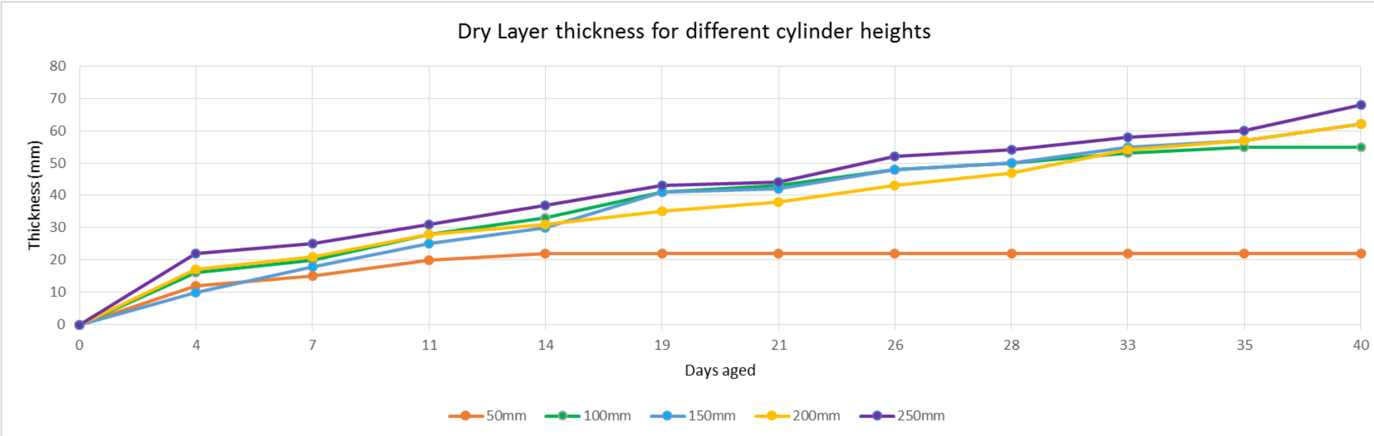

Figure 4: Dry Layer thickness for different cylinder heights

After 40 days of aging the manure in the open air the 50, 100, 150, 200 and 250 mm containers had a manure dry layer thickness of 22, 55, 61, 62 and 68 mm respectively. The thickness of the dry manure layer is dependent on the height of the containers. The 50 mm container had a dry layer thickness of 22 mm as well as empty space (28 mm) as the manure shrunk inwards and reduced in size (see figure 42 in the appendix). The weight loss for the different cylinder heights is illustrated in figures 5 and 6 in terms of mass and percentage respectively.

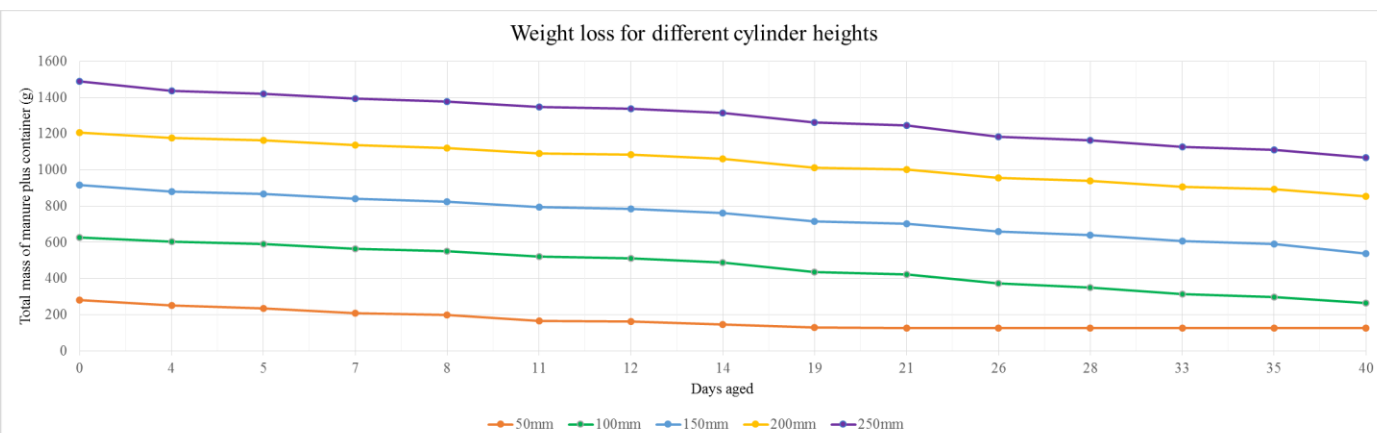

Figure 5: Weight loss for different cylinder heights

The drying of agricultural products can be described by typical drying curves that illustrate the temperature, drying rate and moisture ratios as a function of time. These curves are divided into the constant rate, first falling rate and second falling rate periods as a function of time [56]. The drying of the 100, 150, 200 and 250 mm containers follow the constant rate period (figure 5) during which drying occurs as if pure water is being evaporated. During the constant rate period the physical form of the manure is affected and especially the surface of the manure, caused by capillary and gravity forces [56]. After 14 days of drying the 50 mm container started to move to the first falling rate period when the moisture content decreased to its critical moisture content and there was little to no further weight loss. The moisture movement in the 50 mm container was thus controlled by external-internal resistance or by either external or internal resistance to heat and mass transfer [56]. The drying of poultry manure was studied by Ghaly and MacDonald [57] and they found that the diffusion coefficient increased with both temperature and depth of drying layer, but did not show a linear increase with either variable.

The weight loss was independent of cylinder height and the water evaporated almost linearly for all the containers, except for the 50 mm container (which had dried to constant mass) over 40 days as seen in figure 5. The 50, 100, 150, 200 and 250 mm containers had weight losses of 156, 362, 377, 354 and 420 gram respectively. The weight loss within the manure is shown in figure 6 as a percentage of the initial mass of the manure. The weight loss after 40 days was 56, 58, 41, 29 and 28 % for the 50, 100, 150, 200 and 250 mm containers respectively as a percentage of the initial mass. It is noted that the 50 mm container had the highest percentage of weight loss. This is because the 50 mm height container was completely dry after 40 days. If the 100, 150, 200 and 250 containers were left long enough they too would dry out completely and have higher percentages of weight loss.

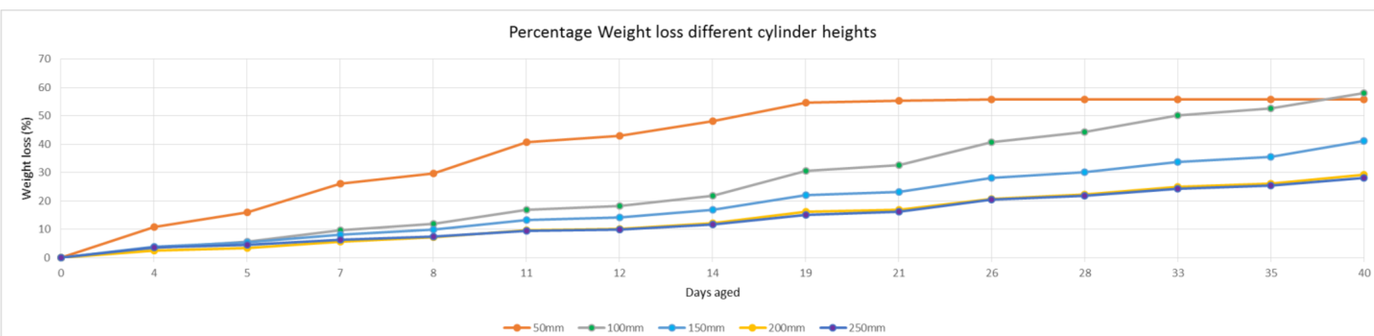

Figure 6: Percentage weight loss for different cylinders

The percentage weight loss is inversely proportional to the height of the containers as it is portrayed in figure 6. The 50 mm and 100 mm containers had the highest percentages weight loss of 56 and 58 % respectively, whereas the higher 150, 200, and 250 mm containers had the lowest percentage of weight loss at 41, 29 and 28 % respectively. After 40 days the 100, 150, 200 and 250 mm containers still contained water within the manure and there was a clear distinction between the dry manure and the wet manure by visual inspection and weight loss.

The drying mechanism can be described by diffusion, liquid/vapour diffusion and capillary action within the porous region of the manure, but diffusion has been widely reported as the dominant mechanism of moisture removal [56]. The nature of the manure and the moisture content determines the rate of diffusion through the porous media represented by the manure. However, the drying mechanism can change due to changes in the physical structure of the manure as it dries.

Figure 7 indicates the average 24 hour profile of the air temperature and the relative humidity at the sample location. The air temperature and humidity had a direct influence on the drying of the manure as indicated in figure 6. Figure 7 is used as an illustration to outline the average ambient conditions that the samples were exposed to and as a result the weight loss that took place as indicated in figure 6. The relatively low ambient temperatures had an effect on the drying rate and thus drying took place at a slower rate than it would have in the hotter summer days. The drying process took place during the winter months of South Africa, 21 July 2015 to 01 September 2015. During this period the air temperature reached a minimum of 11 °C and a maximum of 23 °C on average. The corresponding relative humidity was at a low of 25 % and a high of 58 % on average. The average wind speed was recorded to be between 2 and 3 m/s and the barometric pressure was recorded as 87 kPa on average. There was no rainfall recorded for the period.

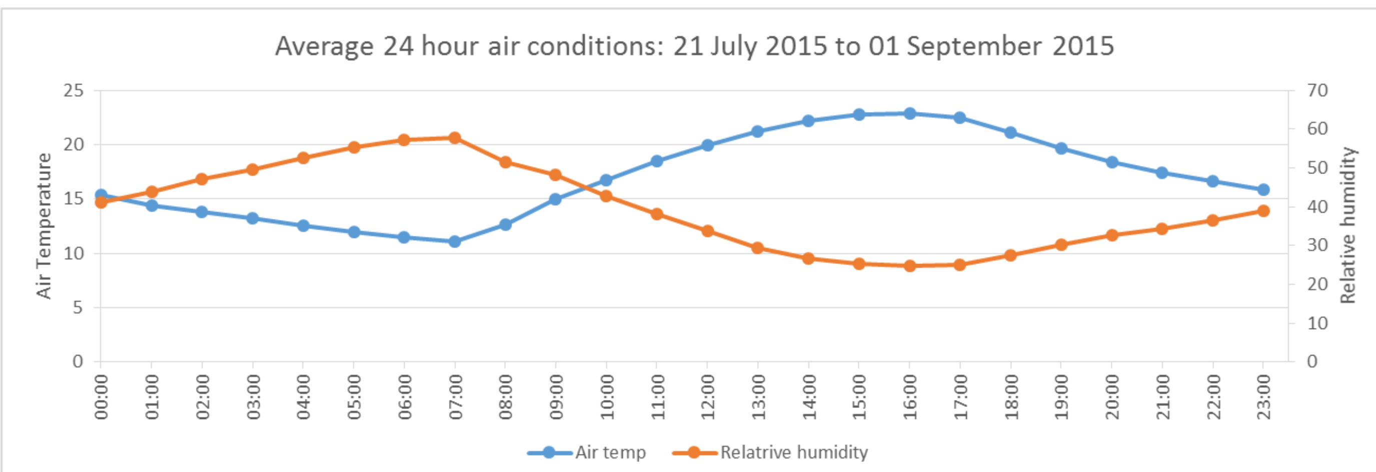

Figure 7: Average 24 hour air conditions - 21 July 2015 to 01 September 2015

5.3 TS, VS and CP of manure in manure samples

Table 5 describes the composition of the sample of manure in terms of TS, VS and CP as the manure was aged for up to 40 days. Only the 150 mm containers were analysed for TS, VS and CP as only these samples were analysed in the BMP test. The first column also distinguishes between samples that were frozen and those that were not. The fresh manure sample had no weight loss and was used as a control. After 40 days the manure had lost 41 % of its initial mass, this was one of the duplicate samples used to measure the TS, VS and CP of the manure samples. The TS and VS results are shown graphically in figure 8.

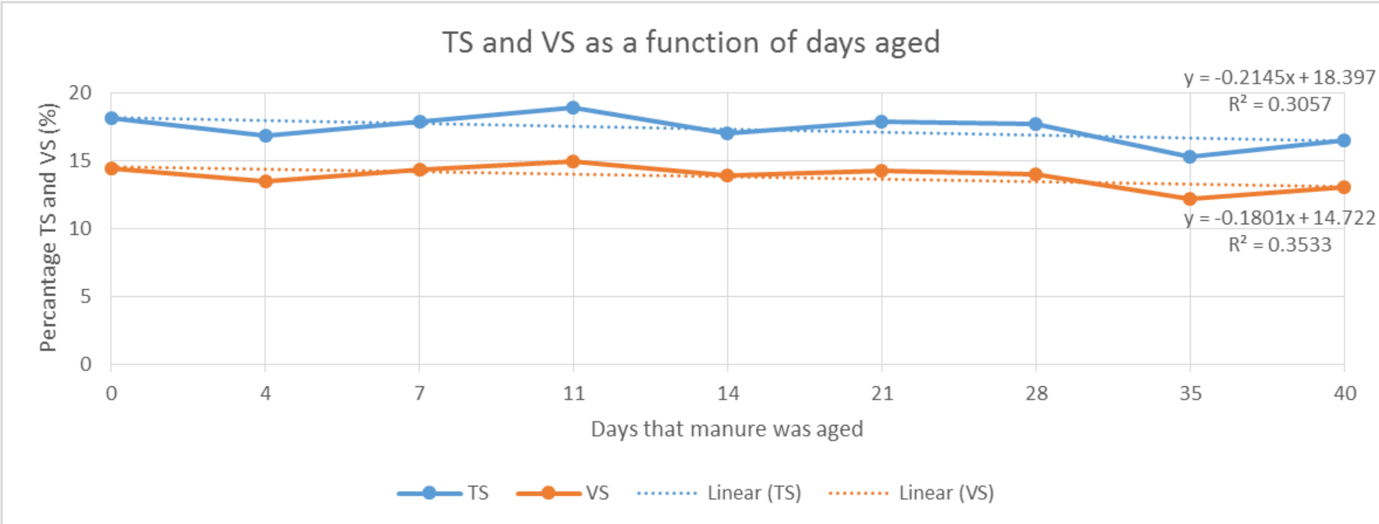

Figure 8: Manure TS and VS as a function of days aged

The TS and VS were plotted as a function of the number of days that the manure sample was aged as indicated in figure 8. Linear regression was applied through the data points with a trend line showing the linear correlation between the different data points. The trend lines had a slightly negative slope of -0.21 and -0.18 for both the TS and VS respectively. The TS and VS had a correlation coefficient of 0.30 and 0.35 respectively, which was low due to experimental errors. This was an indication that there was a slight decrease in TS and VS after the manure was aged for 40 days.

After drying the 150 mm containers for 40 days, there was a weight reduction of 41%. This reduction in weight of the containers was assumed to be water loss together with bacterial activities converting biomass to gas. The anaerobic as well as aerobic breakdown of the manure took place while the manure was being aged. The loss in weight of the containers was accounted for by adding distilled water to the AD process. This would ensure that each biogas digester would have more or less the same amount of TS within the digester. Thus the variance in VS within the biogas digesters would be the only variable determining the difference in biogas production. Therefore the actual mass of manure that was placed in the biogas digester (in the BMP test) for the 40 days aged manure was much less than the mass of fresh manure.

This would have an influence in the biogas produced by the individually aged manures. Due to the fact that the weight percentage loss was accounted for by adding the same amount of distilled water according to the weight that was lost, the amount of biogas in terms of VS would vary to a small extent and produce different amounts of biogas. Therefore the older manure samples might produce the same amount of biogas than the fresher manure samples in terms of actual volume but relatively more when indexed to the VS contained within the manure.

The nitrogen and CP content of all the samples is almost constant at an average of 2.5 and 15.5 % respectively. There was some microscopic breakdown of the manure but as the time of aging was short, the deterioration of the manure was minimal. It must also be noted that the manure had a dry layer on top and that the manure below it was still wet. The wet manure under the dry layer was still decomposing anaerobically as gas pockets were observed to form in the containers. The analysed manure was thus a mixture of dry and wet manure when the sample was homogenised before the BMP test.

Table 5: TS, VS and CP in manure samples as a percentage of the original mass

Days aged	**Drying weight loss (%)**	**TS in sample (%)**	**VS in sample (%)**	**Inorganics in sample (%)**	**VS as a % of TS (%)**	**Nitrogen in sample (%)**	**CP in sample (%)**
0, NF	0.0	18.2	14.4	3.7	79.5	2.4	15.3
0, F	0.0	18.2	14.4	3.7	79.5	2.4	15.3
4, F	3.8	16.8	13.4	3.4	79.9	2.5	15.5
7, F	8.2	17.9	14.4	3.5	80.4	2.4	14.7
11, F	13.3	18.9	14.9	4.0	79.0	2.4	15.1
14, F	16.9	17.0	13.9	3.1	81.5	2.4	15.0
21, F	23.3	17.8	14.2	3.6	79.8	2.5	15.5
28, F	30.1	17.7	14.0	3.7	79.0	2.6	16.1
35, F	35.6	15.3	12.1	3.1	79.6	2.6	15.9
40, F	41.2	16.5	13.1	3.4	79.4	2.5	15.9
40, NF	41.2	15.6	12.3	3.3	78.7	2.6	16.3

5.4 Biogas produced – BMP results

This section describes the results of the BMP test. The figures and tables that follow will focus on the accumulated net biogas formation of all the different manure samples as well as the volumes of methane and carbon dioxide over time. The different manure samples were:

- fresh manure not frozen (fresh NF)
- fresh manure frozen (fresh frozen)
- 4 days aged manure frozen (4 D F)
- 7 days aged manure frozen (7 D F)
- 11 days aged manure frozen (11 D F)
- 14 days aged manure frozen (14 D F)
- 21 days aged manure frozen (21 D F)
- 28 days aged manure frozen (28 D F)
- 35 days aged manure frozen (35 D F)

- 40 days aged manure frozen (40 D F)
- 40 days aged manure not frozen (40 D NF)

These manure samples are all from the same sample of manure and the only difference between the samples is the time they were aged (weight loss), frozen samples and samples that were not frozen. The fresh manure that was not frozen and the manure aged to 40 days and not frozen were both seeded with different rumen sources. The frozen manure samples were all seeded with the same rumen source. Three rumen sources taken on different days were thus used to seed the digester bottles with anaerobic bacteria to speed up the AD process.

The fresh manure sample that was not frozen was analysed for 85 days and showed no measurable gas formation after 41 days. Through the information gathered from the behaviour of the fresh manure that was not frozen it was decided to end the BMP test after 41 days for all the other samples. It was also observed that most of the biogas was produced within the first 5 days after the start of the BMP test. This would also confirm that the rumen fluid sped up the AD process by introducing the anaerobic bacteria into the digester bottles.

The fresh manure sample that was not frozen was used as the control sample which all other samples were measured against. The different manure samples were analysed for the AD process performance in terms of accumulated biogas volume produced and the quality of the biogas in terms of CH_4 (methane) and CO_2 (carbon dioxide) percentages and volumes respectively. The average biogas that was measured from the duplicate rumen sample without manure was then subtracted from the accumulated average biogas formation of that specific digester containing the same rumen sample and manure.

Figure 9 indicates the accumulated average biogas produced from all the different manure samples after 41 days of AD. The biogas volume was expressed as normal millilitres per gram VS (Nml/g.VS) that would account for the daily fluctuations in temperature. The fresh manure that was not frozen produced an accumulated biogas volume of 205 Nml/g.VS. The minimum and maximum biogas volumes were 154 and 369 Nml/g.VS for 11 days aged manure and 35 days aged frozen manures respectively. Almost all of the biogas for all the samples formed in the first 10 days of AD, with very little to no biogas formation after 10 days of AD. The most biogas was observed to have formed between day 1 and 5 of AD for all the samples.

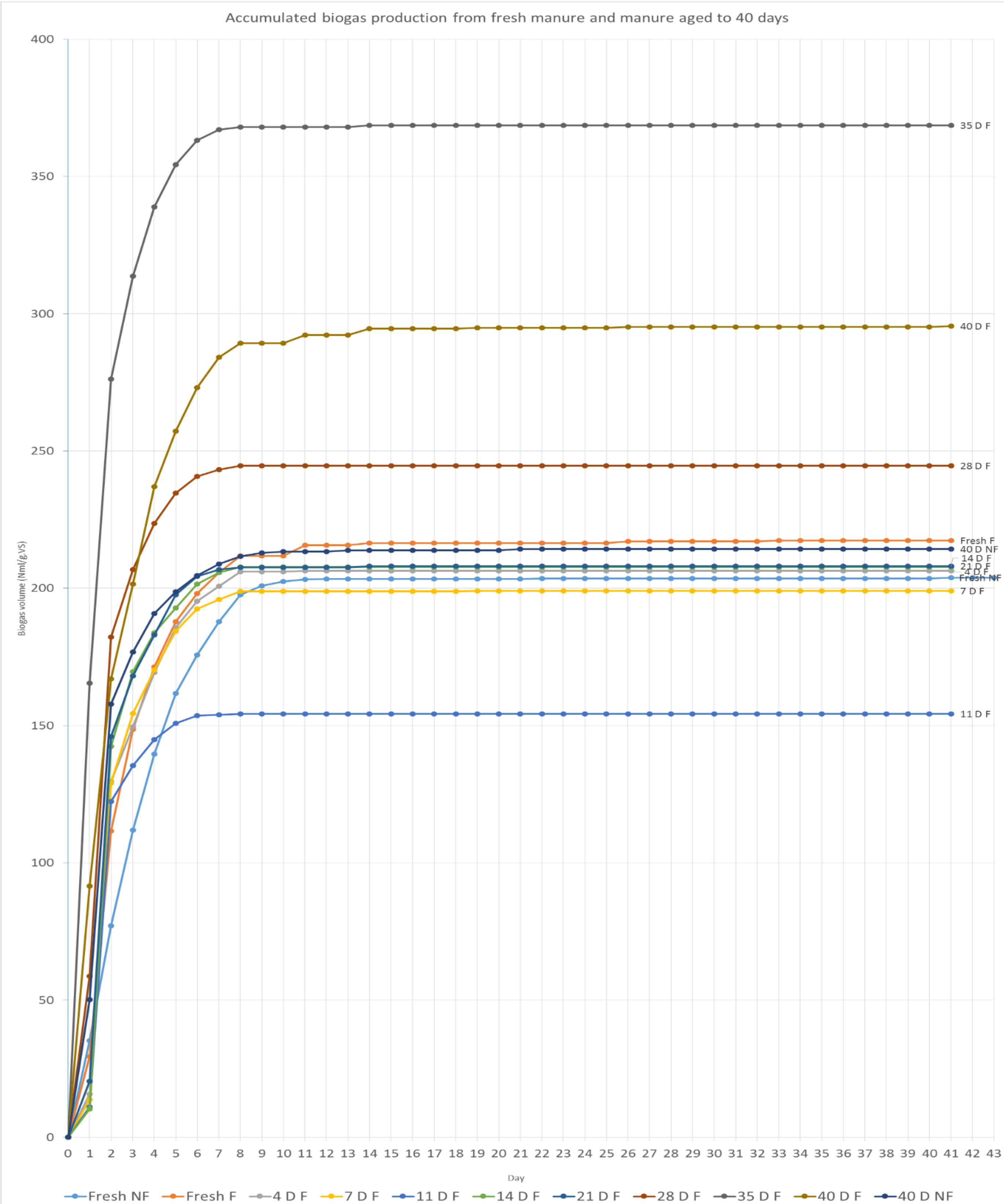

Figure 9: Accumulated biogas production for manure samples from fresh to 40 days aged

In figure 10 the total biogas generated (average of each duplicate sample) as well as the total methane and total carbon dioxide for all the samples of manure after 41 days of AD is shown as a function of the manures age. From this figure it is clear that the samples that produced the most biogas were the 35 days aged manure and the 40 days aged manure that were both frozen. The total methane volumes increased for the older samples after the 21 days aged manure that was frozen whereas the total carbon dioxide volumes remained more or less constant. It is also noted that the total amount of methane is much higher in the older frozen samples than in the fresher samples.

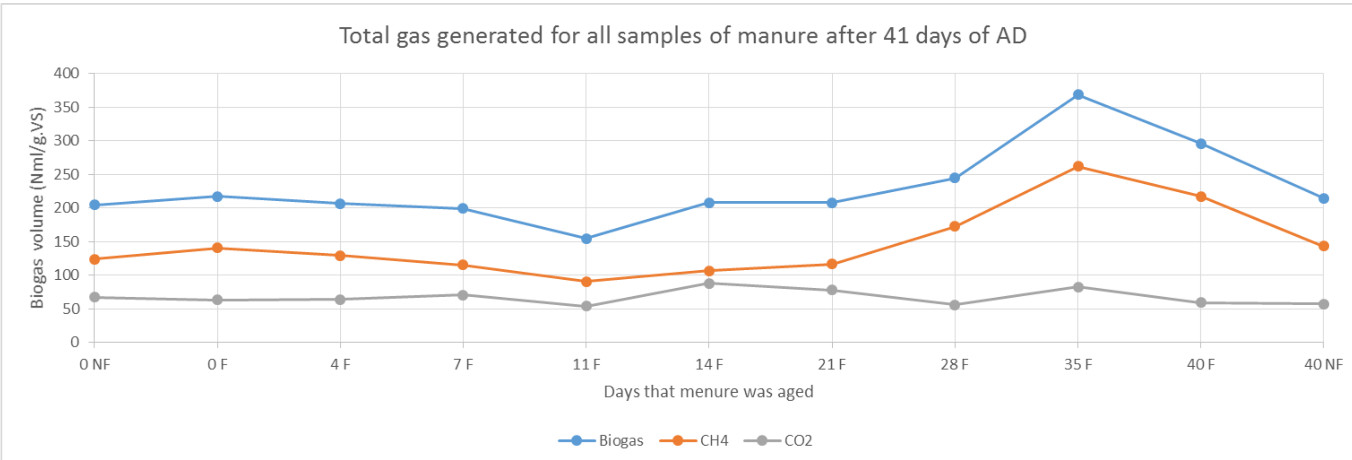

Figure 10: Total gas generated for all samples of manure after 41 days of AD

In table 6 the accumulated biogas volumes (average of each duplicate sample) as well as the total methane and carbon dioxide volumes are shown for all the samples. The table also shows the total methane and carbon dioxide as a percentage and the time required for the sample to produce 80% of its maximum biogas ($t_{80\%}$) over the 41 days of each sample [8]. The $t_{80\%}$ is used as an indication of the evolution of biogas formation over a specific time period. The 40 days aged frozen manure had the highest total methane percentage and the lowest total carbon dioxide percentage at 73 % and 20 % respectively. The 14 days aged frozen manure had the lowest total methane percentage and the highest total carbon dioxide percentage at 51 % and 42 % respectively. The fresh manure that was not frozen had the longest $t_{80\%}$ of 5 days and the 11 days aged manure that was frozen had the shortest $t_{80\%}$ of 2 days. The 11 days aged frozen manure produced the least amount of biogas at 154 Nml/g.VS of which methane was 90 Nml/g.VS and carbon dioxide was 54 Nml/g.VS. The range (digester1 biogas - digester2 biogas) is expressed as a percentage of the average biogas produced between the duplicate digesters. Table 7 indicates the net accumulated biogas produced by each of the duplicate digesters as well as the average net biogas of the duplicate digesters and the range between the two digesters. The results displayed in figures 9 and 10 is the average net biogas, thus it is the average between the duplicate digesters with the gas produced by the inoculating rumen fluid already subtracted. The different rumen samples used to seed the biogas digesters might have had an influence in the performance in biogas production rates and volumes produced.

Table 6: Net accumulated biogas volumes and composition for all manure samples

Days Aged	Accumulated Biogas (Nml/g.VS)	Range (% of average)	Accumulated CH_4 (Nml/g.VS)	Accumulated CO_2 (Nml/g.VS)	Accumulated CH_4 (%)	Accumulated CO_2 (%)	$t_{80\%}$ (days)
0, NF	205	7.9	124	67	61	33	5
0, F	217	14.4	140	63	65	29	4
4, F	206	1.2	129	64	63	31	4
7, F	199	18.1	115	71	58	36	4
11, F	154	7.8	90	54	59	35	2
14, F	208	3.8	106	88	51	42	3
21, F	208	41.6	116	78	56	37	3
28, F	245	2.2	173	56	71	23	3
35, F	369	0.8	262	83	71	22	3
40, F	295	4.5	217	59	73	20	4
40, NF	214	0.7	143	57	67	27	3

Table 7: Net average accumulated biogas volumes of the duplicate digesters

Days Aged	Digester 1 Accumulated biogas (Nml/g.VS)	Digester 2 Accumulated biogas (Nml/g.VS)	Average Accumulated biogas (Nml/g.VS)	Range (% of average)
0 NF	213	196	205	7.9
0 F	233	202	217	14.4
4 F	208	205	206	1.2
7 F	217	181	199	18.1
11 F	160	148	154	7.8
14 F	212	204	208	3.8
21 F	165	251	208	41.6
28 F	247	242	245	2.2
35 F	370	367	369	0.8
40 F	302	289	295	4.5
40 NF	215	213	214	0.7

Table 8 shows the accumulated biogas volumes and composition of the different rumen samples that were used in the AD process. The rumen sample that produced the most biogas was the one used to seed the 40 days aged manure that was not frozen. It produced 116 Nml of biogas and had an accumulated methane and carbon dioxide percentage of 78 % and 16 % respectively. The rumen sample that was used to seed the frozen manure samples produced the least amount of biogas viz. 31 Nml of biogas and had an accumulated methane and carbon dioxide percentage of 61 % and 33 % respectively.

Table 8: Accumulated biogas volumes and composition of different rumen samples used in AD

Rumen sample for	Accumulated Biogas (Nml)	Accumulated CH_4 (Nml)	Accumulated CO_2 (Nml)	Accumulated CH_4 (%)	Accumulated CO_2 (%)
Fresh NF	35	22	10	65	29
All frozen	31	19	10	61	33
40 days NF	116	90	18	78	16

It was also noted that the biogas volume formation of the rumen used for the fresh manure that was not frozen and the rumen used for all frozen samples of manure was more or less the same. The other gasses make up between 6 % and 7 % of the total volume of biogas produced. The other gasses refer to gasses like water vapour, oxygen, nitrogen, ammonia, hydrogen and hydrogen sulphide. The gas formation of the three different rumen samples was also monitored for 41 days and showed no measurable gas formation after 41 days of AD.

The initial pH level within the digester bottles of manure was measured to be 7.0 and after 41 days of AD the pH level of all the digester bottles dropped down to 5.5. This acidic pH level is the reason why the AD process stopped and no more biogas was produced. The digester bottles lost an average of 5 gram in mass after 41 days of AD and it is assumed that the 5 gram loss in mass accounted for the biogas that was produced.

The frozen samples of manure produced higher volumes of biogas than the manure samples that were not frozen. It is conjectured that the freezing process broke down the cell walls of the manure on a microscopic level. When the manure was thawed, the bacteria could break down and convert the VS more easily into biogas than the unfrozen samples of manure. The manure that was aged for 40 days and not frozen produced 214 Nml/g.VS of biogas and the fresh manure that was not frozen produced 205 Nml/g.VS of biogas, considerably less than the 40-day sample that underwent freezing. These results show that the accumulated biogas generated from the fresh manure is approximately the same as the accumulated biogas generated from manure that was aged for 40 days, but also that freezing seems to have a positive effect on gas production. A synergistic effect also seems to be present for drying and freezing, leading to increasing gas production from the samples that were aged (dried) and then frozen. Results also seem to become more reproducible, as indicated by the reduced range in the last column of table 7.

The process of hydrolysis was already initiated while the manure was being aged which broke down the manure on a microscopic level, which caused more favourable conditions for biogas production. When the aged manure samples were thus put through the AD process they produced more biogas than the fresh manure sample. The frozen manure samples indicate that an average of 240 Nml/g.VS of biogas can be produced when the manure is less than 40 days old (but only if similar pre-treatment is used on the manure), with an average methane and carbon dioxide percentage of 63 % and 31 % respectively. Refer to appendix A for plots for each individual sample of manure.

Table 9 contains the experimentally determined kinetic constants of the biogas production rate for the differently aged manure samples. These constants are used in the Gompertz equation (see equation 6) to describe the biogas production rate over time. The experimentally determined rate of biogas production correlates closely to the Gompertz equation rate of biogas production. The correlation coefficient between the experimentally determined biogas production rate and the Gompertz equation biogas production rate ranges between 0.98 and 0.99 for all the differently aged manure samples. The experimentally determined biogas production rate was closely related to the work carried out by Budiyono et al [21] in the sense that rumen fluid seeded to a biogas digester has a significant effect on cumulative biogas production and biogas production rate. Figure 11 indicates the corresponding Gompertz (calculated) correlation fits of biogas production rate compared to the actual experimentally determined biogas production rate as indicated in figure 9.

Table 9: Kinetic constants of biogas production rate for differently aged manure samples.

Days aged	A (ml/g.VS)	U (ml/g.VS.d)	λ (days)	t (days)	Correlation coefficient
0 NF	204.55	41.82	1	41	0.9932
0 F	217.35	82.03	1	41	0.9897
4 F	206.32	113.85	1	41	0.9844
7 F	199	115.32	1	41	0.9901
11 F	154.16	111.34	1	41	0.9945
14 F	207.76	132.21	1	41	0.9922
21 F	208.05	125.53	1	41	0.9910
28 F	244.58	123.48	1	41	0.9820
35 F	368.56	165.43	1	41	0.9553
40 F	295.47	91.47	1	41	0.9804
40 NF	214.22	107.7	1	41	0.9804

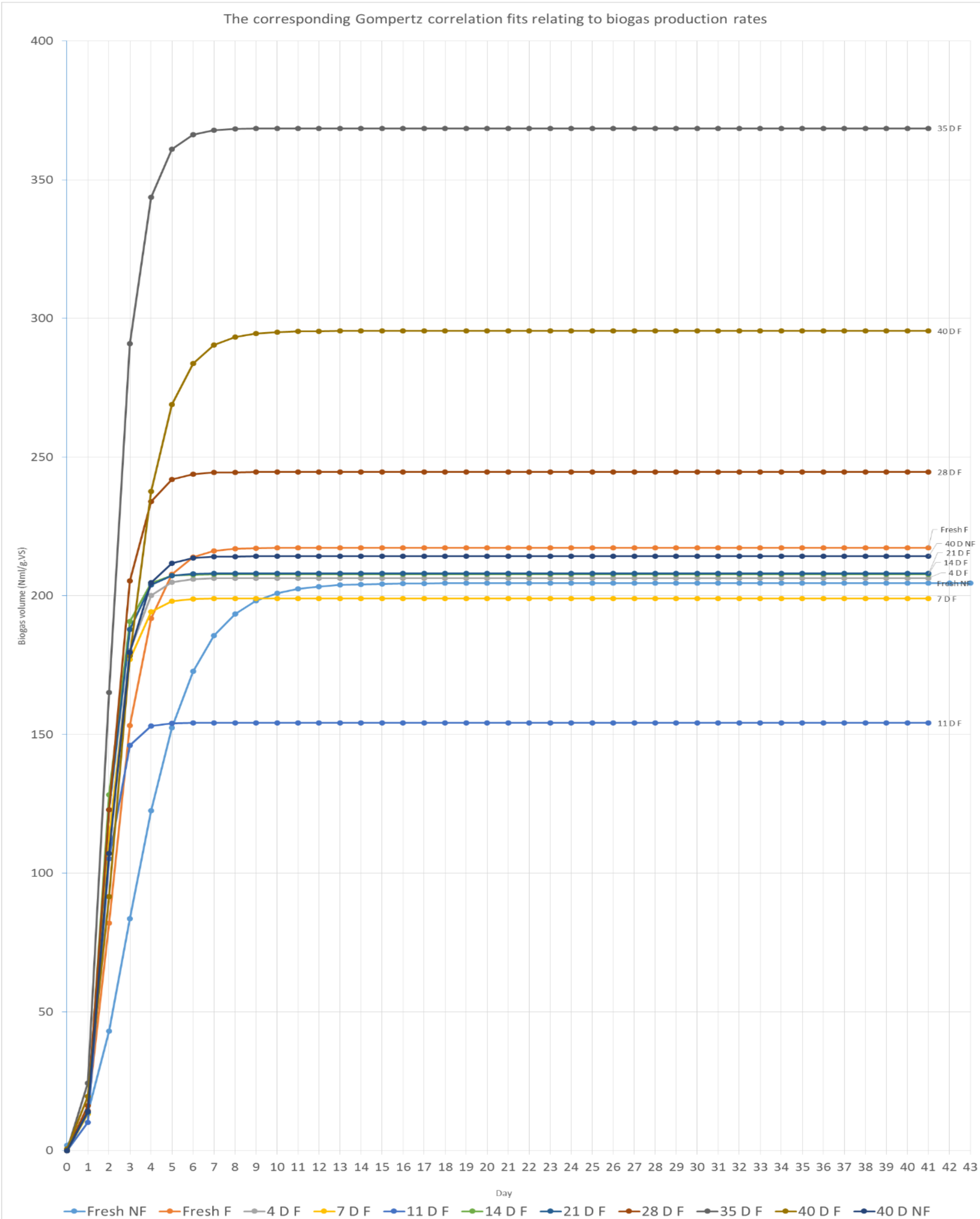

Figure 11: The corresponding Gompertz correlation fits relating to biogas production rates

5.5 Biogas analysis for methane and carbon dioxide content

The biogas quality in terms of methane and carbon dioxide percentages was analysed when biogas was being produced. The bulk of the biogas was formed during the period of day 1 to day 5 and after 10 days of AD the biogas production was minimal. The gas sample that was analysed was taken directly from the digester bottle gas space.

Although there was very little biogas produced after 10 days of AD the methane percentage increased and the carbon dioxide percentage decreased. The biogas quality was measured up until day 26. There was no measurable biogas formation after 41 days of AD. The figures in Appendix B indicate a detailed description of the volume of biogas that was formed in the AD process as well as the percentage of methane and carbon dioxide at that stage in time for all the manure samples. The biogas that was produced from the three different rumen samples as well as their percentage methane and carbon dioxide at that point in time is indicated in the figures below.

Figure 12 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages of the rumen that was used for the fresh manure sample that was not frozen. The biogas volume that was produced on day 1, 5 and 12 was measured to be 12, 0 and 3 Nml respectively. On day 1, 5 and 12 the corresponding methane percentage was measured to be 23, 18 and 86 % and the corresponding carbon dioxide percentage was measured to be 71, 76 and 7 % respectively.

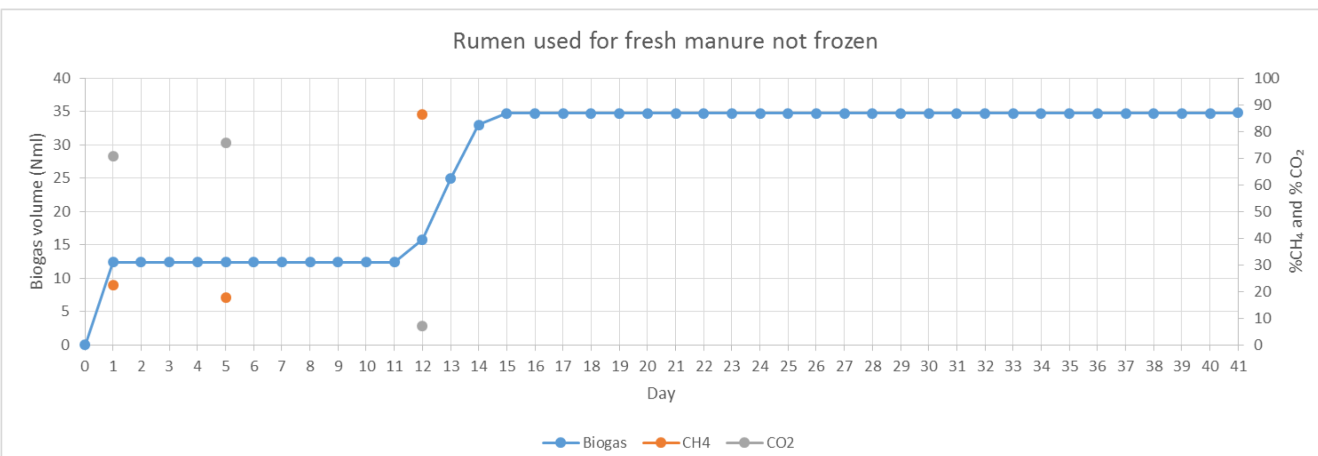

Figure 12: Biogas volume and $\%CH_4$ and $\%CO_2$ of rumen used for fresh manure not frozen

Figure 13 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages of the rumen that was used for all the manure samples that were frozen. The biogas volume that was produced on day 1, 5, 12 and 26 was measured to be 12, 1, 0 and 11 Nml respectively. On day 1, 5, 12 and 16 the corresponding methane percentage was measured to be

21, 18, 86 and 90 % and the corresponding carbon dioxide percentage was measured to be 73, 76, 7 and 4 % respectively.

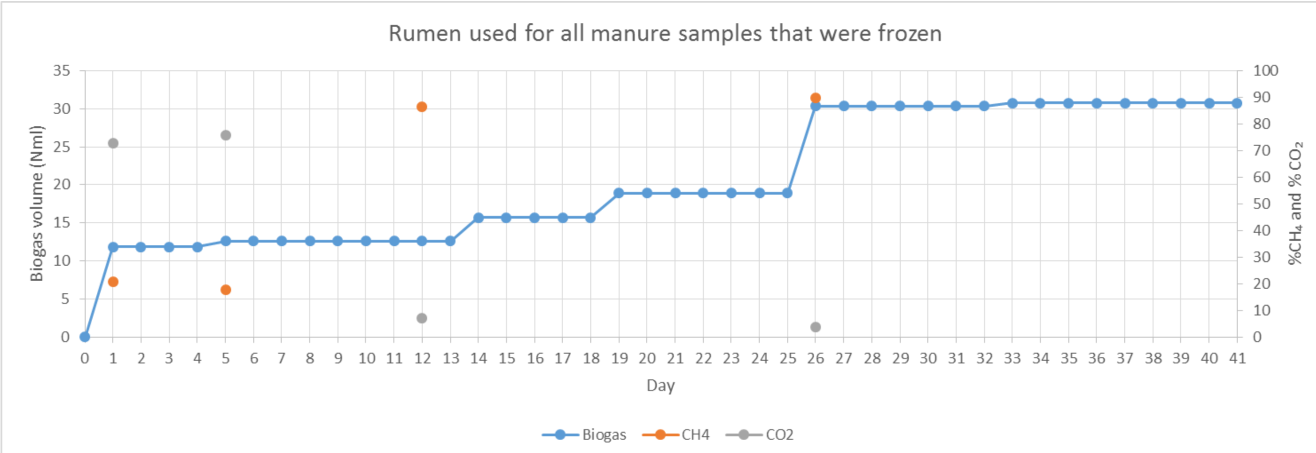

Figure 13: Biogas volume and $\%CH_4$ and $\%CO_2$ of rumen used for all manure samples that were frozen

Figure 14 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages of the rumen that was used for the manure sample that was aged for 40 days and not frozen. The biogas volume that was produced on day 1, 5, 13 and 21 was measured to be 11, 0, 32 and 28 Nml respectively. On day 1, 5, 13 and 21 the corresponding methane percentage was measured to be 23, 17, 89 and 89 % and the corresponding carbon dioxide percentage was measured to be 71, 76, 4 and 4 % respectively.

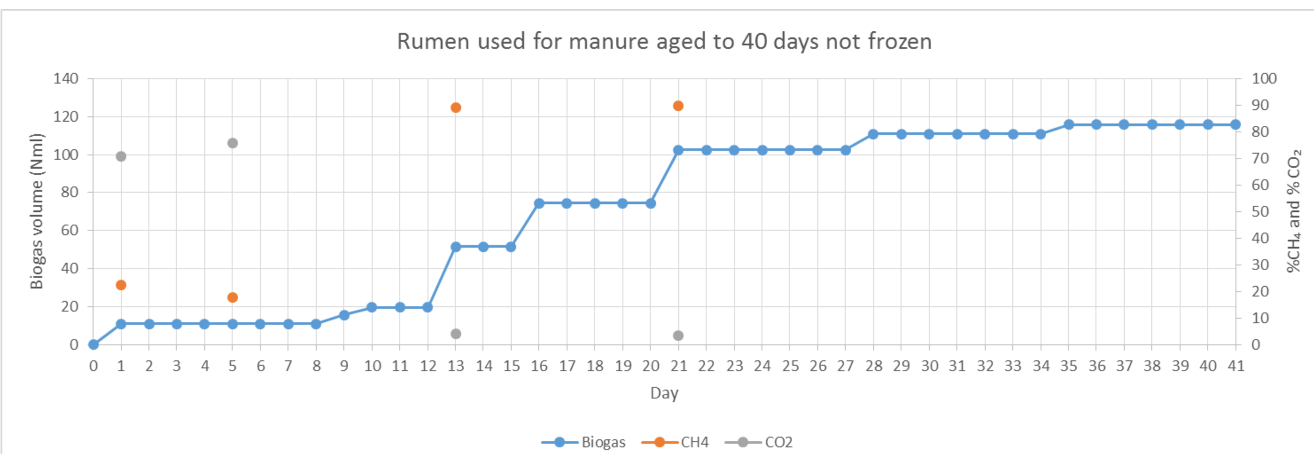

Figure 14: Biogas volume and $\%CH_4$ and $\%CO_2$ of rumen used for manure aged to 40 days not frozen

It can be seen from figures 12 to 14 that for the first 5 days of AD more carbon dioxide is produced than methane. However after 5 days of AD there is a metabolic switch and more methane is produced than carbon dioxide. This observation was an indication that the anaerobic bacteria that produce methane became more metabolically active over time. Thus methane producing bacteria consumed carbon dioxide to produce more methane.

The methanogenic phase is the fourth and final phase in the AD process and methane production takes place under strictly anaerobic conditions (carbonate respiration). The carbon in the biomass is converted into carbon dioxide dissolved in water $(HCO_3^- + H_2)$ and methane [2]. The methane is produced from acetate and/or carbon dioxide through the methanogenic phase bacteria. Thus the carbon dioxide is consumed by the methanogenic bacteria in order to produce more methane. The methanogenic bacteria compete with other microorganisms to consume more H_2 to produce methane. The reduction of $CO_2 + H_2$ only produces 27-30 % of the methane whereas 70 % arises from acetate during methanation [2].

5.6 Conclusion

Five manure samples were placed in containers with stack heights of 50, 100, 150, 200 and 250 mm and analysed for weight loss and the thickness of the top dry layer of manure formation. The samples were analysed for 40 days and the weather conditions were monitored. After 40 days of aging the manure in the open air the 50, 100, 150, 200 and 250 mm containers had a manure dry layer thickness of 22, 55, 61, 62 and 68 mm respectively.

The weight loss was independent of cylinder height and the water evaporates almost linearly for all the containers over 40 days. The weight loss after 40 days was 56, 58, 41, 29 and 28 % for the 50, 100, 150, 200 and 250 mm containers respectively as a percentage of the initial mass. The percentage weight loss is inversely proportional to the height of the containers.

The fresh manure that was not frozen, fresh manure that was frozen, manure aged to 4, 7, 11, 14, 21, 28, 35, 40 days that was frozen and manure aged to 40 days and not frozen were analysed. The samples were analysed for TS, VS, CP and biogas formation as well as the methane and carbon dioxide content within the biogas. There was very little variation in TS, VS and CP for all the samples and the BMP test revealed the difference in biogas formation for the samples.

The digester bottles were seeded with rumen fluid that acted as an inoculant to introduce the anaerobic bacteria into the system and speed up the AD reactions. The gas generation rate was determined over a period of 41 days until there was no measurable biogas formation. Most of the biogas formulated within the first five days of the BMP test. The experimental results of the biogas production rate closely followed the Gomperts correlation fits of biogas production rate. The manure samples had a $t_{80\%}$ of 3 to 4 days in which 80 % of the total biogas volume was produced. The accumulated biogas volume as well as the accumulated methane and carbon dioxide percentages was measured as follows:

- fresh manure not frozen – 205 Nml/g.VS, 61 % CH_4 and 33 % CO_2
- fresh manure frozen – 217 Nml/g.VS, 65 % CH_4 and 29 % CO_2
- 4 days aged manure frozen – 206 Nml/g.VS, 63 % CH_4 and 31 % CO_2
- 7 days aged manure frozen – 199 Nml/g.VS, 58 % CH_4 and 36 % CO_2
- 11 days aged manure frozen – 154 Nml/g.VS, 59 % CH_4 and 35 % CO_2
- 14 days aged manure frozen – 208 Nml/g.VS, 51 % CH_4 and 42 % CO_2
- 21 days aged manure frozen – 208 Nml/g.VS, 56 % CH_4 and 37 % CO_2
- 28 days aged manure frozen – 245 Nml/g.VS, 71 % CH_4 and 23 % CO_2
- 35 days aged manure frozen – 369 Nml/g.VS, 71 % CH_4 and 22 % CO_2
- 40 days aged manure frozen – 295 Nml/g.VS, 73 % CH_4 and 20 % CO_2
- 40 days aged manure not frozen – 214 Nml/g.VS, 67 % CH_4 and 27 % CO_2

The frozen manure samples indicate that an average of 240 Nml/g.VS of biogas can be produced when the manure is less than 40 days old. The average methane and carbon dioxide percentage of the biogas was 63 % and 31 % respectively. The accumulated biogas volume of the rumen samples as well as the accumulated methane and carbon dioxide percentages was measured as follows:

- Rumen for fresh manure not frozen – 35 Nml, 65 % CH_4 and 29 % CO_2
- Rumen for all frozen samples – 31 Nml, 61 % CH_4 and 33 % CO_2
- Rumen for 40 days aged manure not frozen – 116 Nml, 78 % CH_4 and 16 % CO_2

CHAPTER 6: Techno-economic study

6.1 Introduction

The previous chapter shows the results of the BMP test and the amount of biogas that can be produced from cattle manure. This chapter outlines the design of an agricultural biogas plant to produce electrical energy and heat energy. A biogas plant can consist of a number of components depending on the type of digester that is used. There are many different types of biogas plants and digesters, but they all operate with the same principle of AD. This design was based on a simple agricultural biogas plant. The design includes the preparation tank, preparation tank pump, biogas digester, heating pipes, heating fluid (water) pump, gasholder, engine and the storage tank for residue.

The economic viability of the biogas plant was investigated in terms of the US$ because of the instability of the ZAR over the past few years. The local prices for technical equipment and construction material is impacted by the ZAR and US$ exchange rate. Capital budgeting techniques were introduced and various assumptions were made for economic viability.

The economics of the biogas plant was based on the annual capital costs, cost of running, operational costs, income and revenue of the biogas plant. The aim of this chapter is to identify and prioritise the variable factors that will affect the outcome of the economic viability of a biogas plant in South Africa

6.2 Design calculations of an agricultural biogas plant

The size of an agricultural biogas plant should be designed based on the number of animals and the area available for the biogas plant. This design was based on a farm that has 7 000 to 8 000 head of cattle at any time and large open space available for a biogas plant. The daily manure yield was adjusted according to Deublein and Steinhauser [2] where 100 GVE (animal units) would yield 5.0 Mg of manure per day, where one GVE would correspond to the liquid manure from 6 beef cattle. The average biogas yield of 240 Nm^3/ton.VS (240 Nml/g.VS) was assumed for the calculations as it was experimentally determined. This was the average biogas produced by manure that ranged from fresh to manure that was aged up to 40 days. The corresponding average TS and VS of the manure samples was measured to be 17 % and 80 % (as a % of TS) respectively. All the design calculations that follows were adopted from the methods as described by Deublein and Steinhauser [2]. Based on some assumptions and the daily biogas rate, the design of a complete biogas plant will be illustrated next.

Table 10: The manure and biogas yields related to an average substrate

Description	Units	Liquid manure from 600 cattle (100 GVE)	Liquid manure from 7 000 cattle
Manure yield per day ($\dot{M}_G$)	Mgd^{-1}	5.0	58.33
TS content	%	17	17
TS yield per day	$kg_{TS}\,d^{-1}$	850	9 920
VS in TS (as a % of TS)	%	80	80
VS yield per day (VS_{BD})	$Kg_{VS}\,d^{-1}$	680	7 930
Biogas yield ($\tilde{V}_{BD}$)	$m^3\,d^{-1}$	240	1 900

The assumptions that were used for the design calculations of the biogas plant were as follows:

7 000 Beef cattle on the farm for calculation purposes

The density of liquid manure is equal to that of water, $\rho_G = \rho_W = 1000$ kg m^{-3}

Liquid manure yield per day $\dot{M}_G = 58\,330$ kg d^{-1}

Biogas yield per day from manure $\tilde{V}_{BD} = 1\,900$ m^3d^{-1}

6.2.1 The preparation tank

The preparation tank was designed to be a semi-underground vertical cylindrical container constructed out of concrete. The preparation tank was designed to hold liquid manure that was produced within $t_{PT} = 10$ days. The volume of air fixtures was accounted for with a factor of $f_{PT} = 1.25$.

The design volume of the preparation tank is:

Equation 13

$$V_{PT} = \dot{M}_G \times \frac{t_{PT}}{\rho_G} \times f_{PT} = \frac{58\,330\,kg}{d} \times \frac{10d}{1000\,kgm^{-3}} \times 1.25 = 729.1\,m^3$$

The relationship between the height and diameter of the preparation tank was taken as $H_{PT}/D_{PT} = 2$. Thus the calculated height was $H_{PT} = 15.5$ m and the diameter was $D_{PT} = 7.7$ m.

6.2.2 The preparation tank pump

The preparation tank will be equipped with a submersible centrifugal pump that will be able to deliver $\tilde{V}_{VP}$ = 10 m^3/h of liquid manure to the biogas digester. The pump will also be used to pump the complete volume of the biogas digester (V_{BD} = 364.6 m^3 as calculated below) within t_{VP} = 30 h (given below). The efficiency of the pump is assumed to be η_{VP} =0.5 and the pressure head will be ΔP_{VP} = 100 kPa.

The pump throughput:

Equation 14

$$(\tilde{V}_{VP})_1 = 10\frac{m^3}{h} \quad \text{or} \quad (\tilde{V}_{VP})_2 = \frac{V_{BD}}{t_{VP}} = \frac{364.6m^3}{30\ h} = 12.2\ m^3h^{-1}$$

The pump motor capacity:

Equation 15

$$(P_{VP})_1 = (\tilde{V}_{VP})_1 \times \frac{\Delta P_{VP}}{\eta_{VP}} = 10\frac{m^3}{h} \times \frac{1h}{3600\ s} \times \frac{100\ kPa}{0.5} = 0.6\ kW$$
$$(P_{VP})_2 = (\tilde{V}_{VP})_2 \times \frac{\Delta P_{VP}}{\eta_{VP}} = 12.2\frac{m^3}{h} \times \frac{1h}{3600\ s} \times \frac{100\ kPa}{0.5} = 0.7\ kW$$

6.2.3 The biogas digester

The biogas digester will be a semi-underground vertical cylindrical tank constructed out of concrete. The substrate will have a residence time of t_{BD} = 5 days within the biogas digester, as it was experimentally determined that most of the biogas was produced within the first five days of AD. The volume of air and fixtures in the biogas digester is accounted for with the factor f_{BD} = 1.25. The relationship between the height and diameter of the biogas digester will be taken as $H_{BD} : D_{BD} \approx 1:2$. The time to empty the biogas digester will be t_{BD1} = 5 h at a flow rate of υ_{BD1} = 0.5 ms^{-1}.

The biogas digester will be equipped with two propeller agitators (diameter D_{PA} = 0.5 m, Newton number Ne = 0.5, Revolutions n_{PA} = 100 rpm). These agitators will be used for intermittent mixing and breaking off the floating layer with a working period of t_{PA} = 5 min h^{-1}. The agitators will be equipped with submersible motors and their height will be adjusted with retractable chains. Assuming the flow of diluted (to 7 % TS) biomass is $\dot{M}_G$ = 58 330 kg d^{-1}.

The volume of the biogas digester:

Equation 16

$$\mathrm{V_{BD}} = \frac{\dot{\mathrm{M}}_G}{\rho_G} \times t_{BD} \times \mathrm{f}_{VBD} = \frac{58\ 330 kgd^{-1}}{1000\ kgm^{-3}} \times 5d \times 1.25 = 364.6\ m^3$$

The biogas digester will be designed to have a height of H_{BD} = 4.9 m and a diameter of D_{BD} = 9.8 m. The VS loading is assumed to be VS_{BD} = 7 930 kg_{VS} per day.

The volume loading rate of VS into the biogas digester is:

Equation 17

$$\mathrm{B_{BD}} = \frac{VS_{BD}}{V_{BD}} = \frac{7\ 930\ kg_{VS}d^{-1}}{364.6\ m^3} = 21.8\ kg_{VS}m^{-3}d^{-1}$$

Diameter of biogas digester discharge pipe:

Equation 18

$$D_{DP} = \sqrt{\frac{V_{BD}}{t_{BD1} \times v_{BD1}} \times \frac{4}{\pi}} = \sqrt{\frac{364.6\ m^3}{5\ h \times 3600\ s \times 0.5\ m\ s^{-1}} \times \frac{4}{\pi}} \approx 0.23\ m$$

The rated power per agitator drive of the biogas digester:

Equation 19

$$\begin{aligned} P_{PA} &= 1.3Ne \times \rho_G \times n_{PA}^3 \times D_{PA}^5 = 1.3 \times 0.5 \times 1000\ kgm^{-3} \times \left(100 \times \frac{\pi}{30}\right)^3 \times 0.5^5 m^5 \\ &= 23.3\ kW \approx 25\ kW \end{aligned}$$

The average power consumption of both agitators when operated for five minutes every hour:

Equation 20

$$(P_{PA})_{tot} = 2P_{PA} \times t_{PA} = 2 \times 25\ kW \times \frac{300\ s}{3600\ s} = 4.2\ kW$$

6.2.4 The heating pipes

The anaerobic digestion process will be kept under mesophilic temperature conditions where a high mesophilic temperature of T_{BD} = 50 °C is chosen as a design parameter. The assumed lowest outside temperature in winter is T_A = 0 °C (humid soil). The substrate has a specific heat capacity of Cp_{su} = 4.2 KJ kg^{-1} K^{-1} and must be heated from 20 °C to 50 °C, thus the temperature difference is ΔT_{SU} = 30 K.

The walls of the biogas digester will be insulated with a S_{BD} = 0.1 m thick layer of polystyrene with a heat transfer coefficient of α_{BD} = 0.05 $Wm^{-1}K^{-1}$. The assumption is made that heat transfer coefficient is very low through the ceiling thus it is negligible because the ceiling is in contact with gas inside and air outside [2]. It is assumed that the heat transfer coefficient of the wet agitated liquid in the digester is α_i = 4000 $Wm^{-2}K^{-1}$ and that of outside humid soil is α_o = 400 $Wm^{-2}K^{-1}$.

The k-factor is then calculated to be:

Equation 21

$$k_{BD} = \frac{1}{1/\alpha_i + S_{BD}/\alpha_{BD} + 1/\alpha_o} = \frac{1}{1/4000 + 0.1/0.05 + 1/400} = 0.5 \text{ Wm}^{-2}\text{K}^{-1}$$

The maximum temperature difference between the substrate and the environment:

Equation 22

$$\Delta T_{BG} = T_{BD} - T_A = 50 - 0 = 50\ K$$

The heating medium (warm water) will cool from T_{HE} = 60 °C to T_{HA} = 50 °C and the temperature difference is then calculated to be ΔT_W = 10 K. The flow rate of the heating medium will be υ_H = 0.5 ms^{-1}. It is assumed that the heat transfer coefficient inside and outside of the heating pipe is the same, $(\alpha_H)_i = (\alpha_H)_o$ = 400 $Wm^{-2}K^{-1}$, for a slow moving liquid.

The k-factor for the heating pipe wall is then calculated to be:

$$k_H = \frac{1}{1/(\alpha_H)_i + 1/(\alpha_H)_o} = \frac{1}{1/400 + 1/400} = 200 \text{ Wm}^{-2}\text{K}^{-1}$$

The average temperature difference between the heating medium and the substrate in the biogas digester is:

Equation 23

$$\Delta T_H = \frac{T_{HE} + T_{HA}}{2} - T_{BD} = \frac{60 + 50}{2} - 50 = 5\ K$$

The heat required for heating the substrate of the digester:

Equation 24

$$Q_{SU} = \dot{\mathrm{M}}_G \times Cp_{SU} \times \Delta \mathrm{T_{SU}} = \left(\frac{58\ 330\ \mathrm{kgd^{-1}}}{24\ h \times 3600\ s}\right) \times 4.2\ \mathrm{KJ\ kg^{-1}K^{-1}} \times 30\ \mathrm{K} = \ 85.1\ \mathrm{kW}$$

The total surface area of the digester, which conducts heat:

Equation 25

$$A_{BD} = \frac{\pi}{4} \times D_{BD}^2 + \pi \times D_{BD} \times H_{BD} = \frac{\pi}{4} \times 9.8^2 + \pi \times 9.8 \times 4.9 = 224.2\ m^2$$

The heat loss of the biogas digester is:

Equation 26

$$Q_{loss} = k_{BD} \times A_{BD} \times \Delta T_{BD} = 0.5\ \mathrm{Wm^{-2}K^{-1}} \times 224.2 m^2 \times 50\ K = 5.6\ kW$$

Thus the total required heat is:

Equation 27

$$Q_{tot} = Q_{SU} + Q_{loss} = 85.1 + 5.6 = 90.7\ kW$$

The required heating liquid (water) flow rate that supplies heat to the digester:

Equation 28

$$\tilde{\mathrm{V}}_w = \frac{Q_{tot}}{Cp_w \times \rho_w \times \Delta T_W} = \frac{90.7\ kW}{4.2\ KJkg^{-1}K^{-1} \times 1000\ kgm^{-3} \times 10K} = 7.8\ m^3 h^{-1}$$

The diameter of the heating pipe is:

Equation 29

$$D_H = \sqrt{\frac{\tilde{\mathrm{V}}_w}{\upsilon_H} \times \frac{4}{\pi}} = \sqrt{\frac{7.8\ m^3 h^{-1}/3600\ s}{0.5\ m\ s^{-1}} \times \frac{4}{\pi}} \approx\ 0.074\ m$$

The length of the heating pipe is:

Equation 30

$$L_H = \frac{Q_{tot}}{k_H \times \Delta T_H \times \pi \times D_H} = \frac{90.7\ kW}{200\ Wm^{-2}K^{-1} \times 5K \times \pi \times 0.074\ m} \approx 390\ m$$

The Reynold's number of the fluid flow through the heating pipe:

Equation 31

$$Re = \frac{v_H D}{\upsilon} = \frac{0.5ms^{-1} \times 0.074m}{1.31 \times 10^{-6}m^2s^{-1}} = 28\ 300$$

The friction coefficient of the pipe with roughness factor $k = 0.3\ mm$:

Equation 32

$$f_{pipe} = \frac{0.25}{\left[\log\{\frac{k}{3.7 \times D} + \frac{5.74}{Re^{0.9}}\right]^2} = \frac{0.25}{\left[\log\{\frac{0.0003m}{3.7 \times 0.074m} + \frac{5.74}{28\ 300^{0.9}}\right]^2} = 0.03235$$

The pipe loss coefficient due to friction:

Equation 33

$$k_{pipe} = \frac{f_{pipe} \times L_H}{D_H} = \frac{0.03235 \times 390m}{0.074m} = 169.9$$

The dynamic head of the pump:

Equation 34

$$H_D = \frac{K_{pipe}\ \times v_H^2}{2g} = \frac{169.9 \times (0.5ms^{-1})^2}{2 \times 9.81ms^{-2}} = 2.2\ m$$

Assuming that the static head is H_s = 8m then the total head is:

Equation 35

$$H_{tot} = H_D + H_s = 2.2\ m + 8m = 10.2\ m$$

Assuming that the efficiency of the pump $\eta_{HE}\ = 85\%$ then the pump motor power is:

Equation 36

$$P_{HE} = \frac{\tilde{V}_w \times H_{tot} \times g \times \rho}{\eta_{HE}} = \frac{\frac{7.8mh^{-1}}{3600s} \times 10.2m \times 9.81ms^{-2} \times 1000kgm^{-3}}{0.85} = 0.25\ kW$$

6.2.5 Gas holder

The gas holder will be made from plastic foil and it is designed for low-pressure applications. The biogas digester and the gasholder will have a ration of $V_{BD} : V_G = 1 : 2$.

The volume of the gasholder is:

Equation 37

$$V_G = V_{BD}/(V_{BD}/V_G) = 364.6/(1/2) = 729.1\ m^3$$

6.2.6 Engine

The plant will be equipped with an ignition oil diesel engine in the CHP; the ignition oil will be added to the biogas in a ratio of $\dot{M}_{oil} : \dot{M}_B = 0.08$. The biogas has an energy content of E_B = 6 kWh m^{-3} [2]. The ignition oil has an energy content of E_{oil} = 10 kWh per kg of ignition oil. The engine has an efficiency of η_{el} = 30 % to convert mechanical energy to electrical energy and a thermal efficiency of η_{th} = 50 %. Assuming the density of the biogas is ρ_B = 1.25 kgm^{-3} then the consumption of ignition oil is:

Equation 38

$$\dot{M}_B = \tilde{V}_{BD} \times \rho_B = 1\,900\ m^3 d^{-1} \times 1.25\ \text{kg m}^{-3} = 2\,380\ kg\ d^{-1}$$

$$\dot{M}_{oil} = \dot{M}_B \times (\dot{M}_{oil}/\dot{M}_B) = 2\,380 \times 0.08 = 190.4\ kg\ d^{-1}$$

The energy yield of the biogas is then calculated to be:

Equation 39

$$E_{tot} = E_B \times \tilde{V}_{BD} + E_{oil} \times \dot{M}_{oil}$$

$$= (6\ kWh\ m^{-3} \times 1\,904\ m^3 d^{-1} + 10\ kWh \times 190.4\ kg\ d^{-1})/24\ hd^{-1} = 555.3\ kW$$

The electrical and thermal energy yield is calculated to be:

Equation 40

$$KE_{el} = E_{tot} \times \eta_{el} = 555.3 \times 0.3 = 166.6\ kW$$

$$KE_{th} = E_{tot} \times \eta_{th} = 555.3 \times 0.5 = 277.7\ kW$$

Thus the engine will have a nominal capacity of E_{CHP} = 220 kW with a reserve of 30%.

The heat required to heat up the biogas digester (90.7 kW) will be recovered from the CHP system which will produce 280 kW of thermal energy. Cooling water will run through the biogas engine and remove heat from the engine, this heated water will then flow through the biogas digester and heat it up to the desired temperatures with a temperature controlled system. Thus 32% of the waste heat will be recovered to heat up the biogas digester. Therefore there will be no energy costs to heat up the biogas digester in the economic analysis of the biogas plant.

6.2.7 Storage tank for residue

The residue tank will be a semi-underground vertical cylindrical tank that is constructed out of concrete. The residue will have a storage time of t_R = 50 days. Some of the water from the residue tank will be returned to the digester at a rate of $\tilde{V}_R$ = 15 m^3d^{-1}. The factor f_R = 1.1 will account for the volume of air and fixtures in the residue storage tank. The height of the residue storage tank will be taken as the same height as the digester height.

The volume of the residue storage tank:

Equation 41

$$V_R = \left(\frac{\dot{M}_G}{\rho_G} - \tilde{V}_R\right) \times t_R \times f_R = \left(\frac{58\,330 kgd^{-1}}{1000 kgm^{-3}} - 15\, m^3 d^{-1}\right) \times 50\, d \times 1.1 = 2\,383\, m^3$$

Thus the residue tank will be designed to have a height of H_R = 4.9 m and a diameter D_R = 24.9 m.

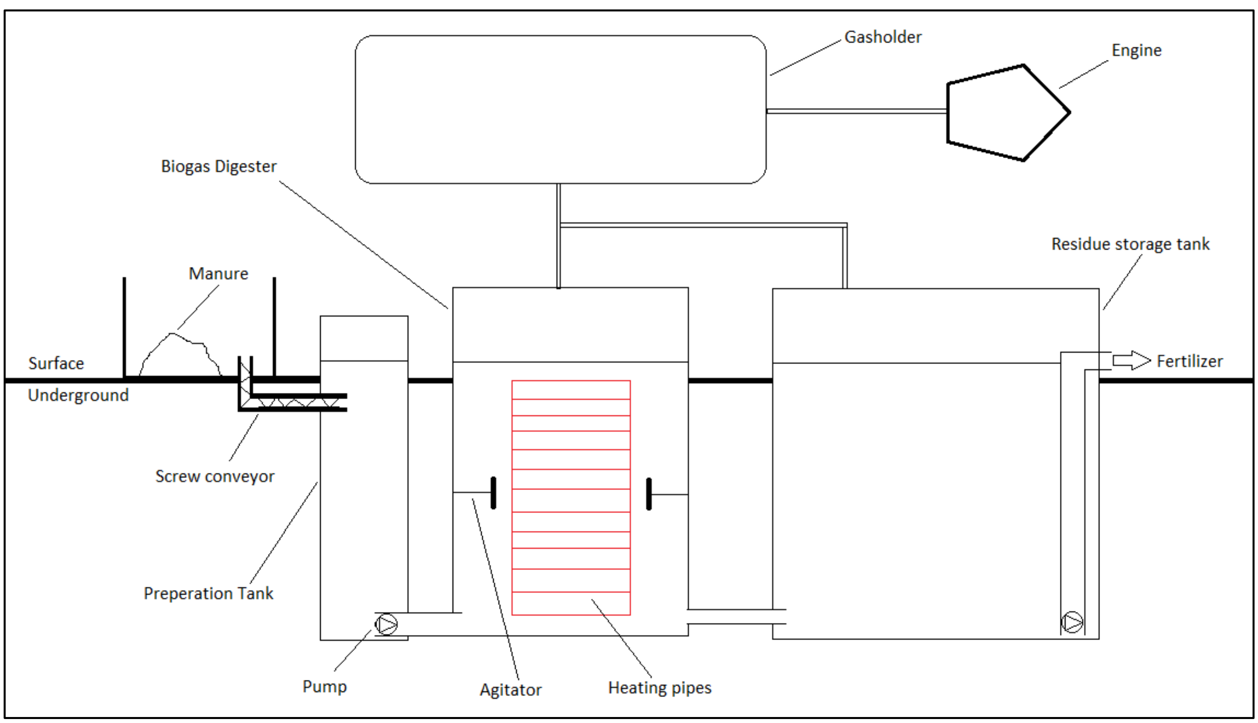

Figure 15 : Simple biogas plant operational layout

Figure 15 indicates the operational layout of a simple agricultural biogas plant. The manure is stored in a storage pit where it is drawn into the preparation tank with a screw conveyor. A submersible pump pumps the liquid manure into the biogas digester where agitators gently mix the manure and the heating pipes keep the manure at constant mesophilic temperatures. The biogas is stored in a gasholder and feeds a gas engine as per the required volume to generate electricity. Once the manure has been in the biogas digester for a sufficient amount of time to extract the maximum amount of biogas it moves to the residue tank for storage and is used as fertilizer as it is required for fertilization of the farm fields.

6.2.8 Total heat and power consumption of the biogas plant

The designed daily energy and heat consumption of the biogas plant is shown in table 11. This is the average designed daily energy and heat consumption of the biogas plant and it is based on the calculations of the previous sections. The average electrical power consumption of the biogas plant will be 5.0 kW and the total heat consumption will be 90.7 kW which will lead to a total CHP consumption of 95.7 kW daily. The pump that will be used to pump the complete volume out of the biogas digester $(P_{VP})_2 = 0.7\ kW$ will only be used in infrequent intervals when it is required to empty the biogas digester for maintenance. Thus the $(P_{VP})_2 = 0.7\ kW$ does not form part of the daily energy consumption of the biogas plant.

Table 11: The calculated CHP consumption of the biogas plant

Energy consumer	Abbreviation	Energy (kW)
Preparation tank pump	$(P_{VP})_1$	0.6
Two agitators	$(P_{PA})_{tot}$	4.2
Pump motor power to pump heating fluid (water)	P_{HE}	0.25
Total power consumption	$\mathbf{E_{el}}$	**5.0**
Digester heat loss	Q_{loss}	5.6
Heat for heating substrate	Q_{tot}	85.1
Total heat consumption	$\mathbf{E_{th}}$	**90.7**

6.3 The economics of a biogas plant in US$

The complete investment cost of a biogas plant can be from US$ 300 - 500 per m^3 volume of the biogas digester [2]. The smaller value refers to large biogas plants and the larger value refers to smaller biogas plants. The estimated operational hours of the biogas plant will be taken as t_s = 8760 ha^{-1} (365 days). The volume of the biogas digester was calculated as V_{BD} = 364.6 $m^3$and the nominal capacity of the CHP was calculated to be E_{CHP} = 220 kW. The economic cost is based on an initial investment of K_{inv} = US$ 182 300 (assuming US$ 500 per m^3 of the digester volume) with an additional K_K = US$ 60 000 that will be considered for the CHP. Thus the total investment that will be considered for the biogas plant will be K_{tot} = US$ 242 300.

6.3.1 The annual capital costs

The concrete works of the biogas plant is assumed to be $\chi_B = K_B/K_{inv}$ = 0.63 of the considered investment costs, which will amortize in t_B = 20 years. The technical equipment costs of the investment will be considered to be $\chi_T = K_T/K_{inv}$ = 0.37, which will amortize in t_T = 15 years. The complete cost of the CHP K_K = US$ 60 000 can be amortized within t_k = 10 years. The total investment cost will have an interest rate of 7 % per annum on the total loan (Z_R = 0.07 a^{-1}).

Then the annual costs for the concrete works is calculated as:

Equation 42

$$K_B = \chi_B \times K_{inv}/t_B = 0.63 \times US\$\,182\,300/20\ a = US\$\ 5\,742\ a^{-1}$$

The annual costs for technical equipment is calculated as:

Equation 43

$$K_T = \chi_T \times K_{inv}/t_T = 0.37 \times US\$\,182\,300/15\ a = US\$\,4\,497\ a^{-1}$$

The annual costs for the CHP:

Equation 44

$$K_{CHP} = K_K/t_k = US\$\,60\,000/10\ a = US\$\,6\,000\ a^{-1}$$

The annual cost for interest:

Equation 45

$$K_{int} = Z_R \times K_{tot} = 0.07\ a^{-1} \times US\$\,242\,300 = US\$\,16\,961\ a^{-1}$$

Then the total annual capital bound cost of the biogas plant will be:

Equation 46

$$K_{cap} = K_B + K_T + K_{CHP} + K_{int} = US\$\ 33\ 200\ a^{-1}$$

6.3.2 The annual cost of running

The cattle manure that is fed into the biogas digester is available free of charge on the farm and thus there is no cost to transport the cattle manure. The designed power consumption of the plant is E_{el} = 5.0 kW, the ignition oil consumption $\dot{M}_{oil}$ = 190.4 kg d^{-1} and the heat consumption E_{th} = 90.7 kW. The heat required to heat up the biogas digester (90.7 kW) will be recovered from the CHP system which will produce 280 kW of thermal energy.

The cost of electricity is taken as Eskom's Megaflex tariff for the 2016-2017 rates in which the averages daily summer rate is R 0.7762 per kWh and the average daily winter rate is R 1.3938 per kWh. Taking the average rand dollar exchange rate as R 15 per US$ for 2016, the average summer tariff is calculated to be K_{sum} = US$ 0.0518 per kWh and the average winter tariff is K_{win} = US$ 0.0929 per kWh. These rates are implemented for 9 months of summer and 3 months of winter according to Eskom's tariff structure. The cost of ignition oil will be assumed to be K_{oil} = US$ 0.20 per kg and the costs for heating will be assumed to be KW_{spec} = US$ 0.04 per kWh [2].

The annual costs for electricity is then calculated to be:

Equation 47

$$K_{el} = \left(E_{el} \times K_{sum} \times t_s \times \frac{9}{12}\right) + \left(E_{el} \times K_{win} \times t_s \times \frac{3}{12}\right)$$

$$= \left(5.0\ kW \times US\$\ 0.0518\ kWh^{-1} \times 8760\ h\ a^{-1} \times \frac{9}{12}\right) + \left(5.0\ kW \times US\$\ 0.0929\ kWh^{-1} \times 8760\ h\ a^{-1} \times \frac{3}{12}\right) = US\$\ 2\ 718\ a^{-1}$$

The annual costs of the biogas engine ignition oil:

Equation 48

$$K_{oil} = \dot{\mathrm{M}}_{\mathrm{oil}} \times K_{oil} \times t_s = (190.4\ kg\ d^{-1}/24\ h\ d^{-1}) \times UD\$0.20\ kg^{-1} \times 8760\ h\ a^{-1}$$

$$= US\$\ 13\ 900\ a^{-1}$$

Thus the total annual cost of running the biogas plant will be:

Equation 49

$$K_{run} = K_{el} + K_{oil} = US\$\ 16\ 617\ a^{-1}$$

6.3.3 The annual operational cost

The annual maintenance cost of the biogas plant will be y_B = 0.5 % of the investment cost for concrete works, y_T = 3 % of the investment cost for technical equipment, and y_{CHP} = 4 % of the investment cost for the CHP. The annual working hours of the personnel that operates the biogas plant is assumed to be t_{pers} = 1 000 h a^{-1} at a rate of K_{pers} = US\$ 10 h^{-1}. The insurance costs of the biogas plant is assumed to be y_{ins} = 0.5 % of the total investment cost.

The annual maintenance costs of the biogas plant for concrete works:

Equation 50

$$KM_{conc} = y_B \times \chi_B \times K_{inv} = 0.005\ a^{-1} \times 0.63 \times US\$\ 182\ 300 = US\$\ 574\ a^{-1}$$

The annual maintenance costs for technical equipment:

Equation 51

$$KM_{tech} = y_T \times \chi_T \times K_{inv} = 0.03\ a^{-1} \times 0.37 \times US\$\ 182\ 300 = US\$\ 2\ 024\ a^{-1}$$

The annual maintenance costs of the CHP:

Equation 52

$$KM_{CHP} = y_{CHP} \times K_K = 0.04\ a^{-1} \times US\$\ 60\ 000 = US\$\ 2\ 400\ a^{-1}$$

The annual personnel costs:

Equation 53

$$KM_{pers} = K_{pers} \times t_{pers} = US\$\ 10\ h^{-1} \times 1\ 000\ h\ a^{-1} = US\$\ 10\ 000\ a^{-1}$$

The annual insurance costs of the biogas plant:

Equation 54

$$KM_{ins} = y_{ins} \times K_{tot} = 0.005\ a^{-1} \times US\$\ 242\ 300 = US\$\ 1\ 212\ a^{-1}$$

Thus the total operational costs of the biogas plant is:

Equation 55

$$KM_{tot} = KM_{conc} + KM_{tech} + KM_{CHP} + KM_{pers} + KM_{ins} = US\$\ 16\ 209\ a^{-1}$$

6.3.4 Total annual costs, income and revenue of the biogas plant

Thus the annual overall total costs of the biogas plant is:
Equation 56

$$KO_{tot} = K_{cap} + K_{run} + KM_{tot} = US\$\ 66\ 026\ a^{-1}$$

The renewable energy feed-in tariff (REFIT) is defined as the approved tariff determined by NERSA (March 2011) for a renewable energy generator in South Africa. The REFIT phases 1 and 2 published in 2011 determined the prices according to the different technologies and cost of electricity. The value of R 0.96 per kWh was assigned for the electrical sales from biogas in 2009. The tariff of R0.96/kWh was to be escalated on an annual basis by the Consumer Price Index (CPI) with base date April 2009 [58]. It was conservatively assumed that, under South African climatic conditions, and due to the location of cattle feedlots in rural areas, no market for waste heat would exist.

Table 12 indicates the REFIT rates for renewable energy sources in South Africa as put out by NERSA (March 2011) and subsidised by the government. Table 13 indicates the biogas REFIT value escalations according to the CPI with base date April 2009 up until April 2016. Thus in 2016 the sales from biogas would have escalated to a REFIT value of R1.39/kWh or K_{refit} = US$ 0.0926/kWh.

Table 12: Renewable energy feed-in tariff structure as put out by NERSA (2009)

Technology	REFIT (R/kWh)
Wind	1.25
Small Hydro	0.94
Landfill gas	0.90
CSP with 6 hours storage	2.1
CSP through without storage	3.14
Large scale grid connected PV	3.94
Solid biomass	1.18
Biogas	0.96
Tower CSP with 6 hours storage	2.31

Table 13: Biogas REFIT value increases according to the CPI with base date April 2009

Year	CPI	Inflation %	REFIT (R/kWh)	REFIT (US$/kWh)
April-2009	83.9	-	0.96	0.0640
April-2010	87.6	4.41	1.00	0.0668
April-2011	91.3	4.22	1.04	0.0696
April-2012	97.0	6.24	1.11	0.0740
April-2013	102.7	5.88	1.18	0.0783
April-2014	109.1	6.23	1.25	0.0832
April-2015	114.0	4.49	1.30	0.0870
April-2016	121.4	6.49	1.39	0.0926

Thus the annual sales of electrical power:
Equation 57

$$KP_{el} = KE_{el} \times K_{refit} \times t_s = 166.6\ kW \times US\$\ 0.0926\ kWh^{-1} \times 8760\ h\ a^{-1}$$
$$= US\$\ 135\ 133a^{-1}$$

The annual sales of digestate as fertilizer is assumed to be:
Equation 58

$$KP_{fert} = US\$\ 5\ 000\ a^{-1}$$

The annual income of the biogas plant is:
Equation 59

$$KP_{tot} = KP_{el} + KP_{fert} = US\$\ 140\ 133\ a^{-1}$$

The annual revenue of the biogas plant is:
Equation 60

$$KP_{rev} = KP_{tot} - KO_{tot} = US\$\ 74\ 107\ a^{-1}$$

The ROI is chosen as an indicator of economic attractiveness of a project in the following simplified form:
Equation 61

$$ROI = \frac{KP_{rev}}{K_{tot}} = \frac{74\ 107}{242\ 300} = 30.6\%$$

Thus the ROI > 13% and is attractive from the commercial point of view and will enter the economic potential of a biogas plant [24].

The NPV of the project was calculated to be:

Equation 62

$$NPV = \left(\sum_{t=1}^{t=20} \frac{US\$\ 74\ 107}{(1+0.07)^n}\right) - US\$\ 242\ 300 = US\$\ 542\ 792$$

The IRR of the project was calculated to be (NPV =0)

Equation 63

$$\left(\sum_{t=1}^{t=20} \frac{US\$\ 74\ 107}{(1+IRR)^n}\right) - US\$\ 242\ 300 = 0$$

$$IRR = 30.4\%$$

The Payback Time (PBT) period of the biogas plant investment:

Equation 64

$$PBT = \frac{KP_{tot}}{KP_{rev}} = \frac{242\ 300}{74\ 107} = 3.3\ years$$

Table 14 indicates the techno economical evaluation of the different manure samples. The design and economic feasibility was calculated by using the same methodology as described in sections 6.2 and 6.3 for the averaged experimental results. The table compares the techno economical evaluation of the average, 0 NF, 11 F, 14 F, 35 F and 40 NF manure samples. The table only indicates the values that change when the manure characteristics was changed in terms of TS, VS and biogas volume produced by the different manure samples. The values that are not in the table remain the same and can be seen in sections 6.2 and 6.3. Thus table 14 provides a comparative techno-economic valuation of the insights into the role that drying has in AD. It is indicated in table 14 that the biogas plant is economically viable for the average, 0 NF, 11 F, 14 F, 35 F and 40 NF manure samples.

Table 14: Techno economic evaluation of manure samples

Description	Unit	**Average**	**0 NF**	**11 F**	**14 F**	**35 F**	**40 NF**
Manure characteristics							
Experimental biogas volume	Nml/g.VS	240	205	154	208	369	214
TS	%	17.0	18.2	18.9	17.0	15.3	15.6
VS (% of TS)	%	80.0	79.5	79.0	81.5	79.6	78.7
Drying weight loss	%	23.0	0.0	13.3	16.9	35.6	41.2
Biogas yield per day ($\tilde{V}_{BD}$)	m^{-3} d^{-1}	1 900	1 730	1 340	1 680	2 620	1 530.0
TS yield per day	kg_{TS} d^{-1}	9 920	10 620	11 020	9 920	8 920	9 100.0
VS yield per day	kg_{VS} d^{-1}	7 930	8 440	8 710	8 080	7 100	7 160.0
Design of biogas plant							
VS loading rate (B_{BD})	kg_{VS} $m^{-3}d^{-1}$	22	23	24	22	20	20
Biogas consumption ($\dot{M}_B$)	kg d^{-1}	2 380	2 160	1 680	2 100	3 280	1 920
Ignition oil ($\dot{M}_{oil}$)	kg d^{-1}	190	173	134	168	262	153
Total power yield (E_{tot})	kW	555	505	391	490	765	447
Electrical power yield (KE_{el})	kW	167	151	117	147	229	134
Thermal power yield (KE_{th})	kW	278	252	196	245	382	224
engine capacity (E_{CHP})	kW	220	200	160	200	300	180
Economics of biogas plant							
Total annual costs (KO_{tot})	US\$ a^{-1}	66 030	64 760	61 920	64 400	71 260	63 310
Electrical power sales (KP_{el})	US\$ a^{-1}	135 130	122 800	95 200	119 310	186 060	108 770
Total annual income (KP_{tot})	US\$ a^{-1}	140 130	127 800	100 200	124 310	191 060	113 770
Total annual revenue (KP_{rev})	US\$ a^{-1}	74 110	63 050	38 280	59 910	119 800	50 460
ROI	%	30.6	26.0	15.8	24.7	49.4	20.8
NPV	US$	542 790	425 600	163 230	392 420	1 026 790	292 270
IRR	%	30.4	25.7	14.8	24.4	49.4	20.3
PBT	Years	3.3	3.8	6.3	4.0	2.0	4.8
Economic feasibility (Y/N)		**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

6.4 Conclusion

The design of the biogas plant was based on 7 000 cattle that would produce 58 330 kg manure per day. The average biogas yield of 240 Nm^3/ton.VS was assumed for calculation purposes of the economic study , together with the average TS and VS content of 17% and 80% (as a % of TS) respectively as it was experimentally determined. The designed total power yield of the biogas plant was 555.3 kW for the CHP. The electrical power of 166.6 kW would be produced from a 220 kW engine and the heat energy produced was 277.7 kW. The total electrical and heat power consumption of the biogas plant was designed to be 5.0 kW and 90.7 kW respectively.

The economic viability of the biogas plant was based on a proposed REFIT value of US$ 0.0926 (R1.39) per kWh for the sales of electrical energy generated from biogas. The annual capital, consumption and operational costs of the biogas plant was calculated to be US$ 33 200, US$ 16 617 and US$ 16 209 respectively. The total annual income and costs of the biogas plant was US$ 140 133 and US$ 66 026 respectively. This leads to an annual revenue of US$ 74 107 for the biogas plant. The ROI = 30.6% (> 13%) and is attractive from the commercial point of view and will enter the economic potential. The NPV, IRR and PBT was calculated to be US$ 542 792, 16% and 6 years respectively. The ROI, NPV, IRR and PBT was the tools used to determine the economic viability of the different manure samples. The weight loss during drying as well as the loss in TS and VS had an impact on the biogas volume produced and in turn the economic viability of each individual sample.

The comparison of the different manure samples showed that the drying process played an important role in the economic viability of the biogas plant. The weight loss of the manure samples during the drying process caused variations in TS and VS which affected the biogas yield and quality. Thus the economic viability of the biogas plant was dependent on the TS, VS and biogas production that was affected by the drying process. The results showed (average, 0 NF, 11 F, 14 F, 35 F and 40 NF) that the biogas plant would depend on a certain drying time to be economically viable. The 11 F and 40 NF manure samples were less economical due to the low income from electrical sales caused by changes in TS, VS and biogas production. Thus the manure aging would impact the overall profitability of the biogas plant due. The economic study was focused on the sales of electric energy and digestate as fertiliser, thus the annual revenue of the biogas plant can be increased if the heat energy can be sold or utilised further. Thus the economic viability of the biogas plant is dependent on the sales of electric and heat energy (utilizing more heat energy) as well as the sales of digestate as fertiliser.

CHAPTER 7: Conclusions and recommendations

7.1 Introduction

This study will be concluded in this chapter with a discussion of the conclusions and recommendations. The emphasis of this study was to investigate the drying process of cattle manure and the biogas yield from manure ranging from fresh cattle manure to manure that has been periodically aged to 40 days. The experimentally determined average biogas yield, TS and VS from the cattle manure was then used to develop a techno-economic model to produce electricity and heat from biogas in South Africa. The biogas plant was designed as a simple agricultural biogas plant. The biogas plant was economically viable with the escalated REFIT value according to the annual CPI increases and shows positive returns for some of the manure samples. There were cases where the aged manure samples produced less biogas due to reduction in TS and VS during the drying process. Further to that the 35 F manure sample produced the most biogas and was the most economical sample even though it had lost 35 % of its initial mass and showed a reduction in TS and VS. This chapter will be concluded by suggestions for future research and finally a summary of the study.

7.2 Main findings

This section reviews the main findings of the study and discusses the contributions of effectively achieving both the primary and secondary objectives. The primary objective of the study was to investigate the amount of biogas that can be produced from cattle manure. The investigation was conducted by first aging the manure to 4, 7, 11, 14, 21, 28, 35 and 40 days respectively and determining their biogas yields by using the BMP test. The manure samples were placed in containers with different heights and analysed for weight loss and the thickness of the dry manure layer formation. The manure samples were all analysed for TS, VS and CP to analyse the nutritional value of the cattle manure. The percentage methane and carbon dioxide in the biogas was measured at least once a week with a GC to monitor the percentage variations of the different samples of biogas over time. It was found that the older/drier manure samples produced a better quality of biogas to a certain extent.

After 40 days of aging the manure in the open air the 50, 100, 150, 200 and 250 mm containers had a manure dry layer thickness of 22, 55, 61, 62 and 68 mm respectively. The weight loss after 40 days was 56, 58, 41, 29 and 28 % for the 50, 100, 150, 200 and 250 mm containers respectively as a percentage of the initial mass. Thus the percentage weight loss was found to be inversely proportional to the height of the containers. There was very little variation in TS, VS and CP for all the samples and the BMP test revealed the difference in biogas formation for the differently aged manure samples.

The manure samples had a $t_{80\%}$ of 3 to 4 days in which 80 % of the maximum biogas volume was produced. The accumulated net biogas volume as well as the accumulated methane and carbon dioxide percentages was measured as follows:

- fresh manure not frozen – 205 Nml/g.VS, 61 % CH_4 and 33 % CO_2
- fresh manure frozen – 217 Nml/g.VS, 65 % CH_4 and 29 % CO_2
- 4 days aged manure frozen – 206 Nml/g.VS, 63 % CH_4 and 31 % CO_2
- 7 days aged manure frozen – 199 Nml/g.VS, 58 % CH_4 and 36 % CO_2
- 11 days aged manure frozen – 154 Nml/g.VS, 59 % CH_4 and 35 % CO_2
- 14 days aged manure frozen – 208 Nml/g.VS, 51 % CH_4 and 42 % CO_2
- 21 days aged manure frozen – 208 Nml/g.VS, 56 % CH_4 and 37 % CO_2
- 28 days aged manure frozen – 245 Nml/g.VS, 71 % CH_4 and 23 % CO_2
- 35 days aged manure frozen – 369 Nml/g.VS, 71 % CH_4 and 22 % CO_2
- 40 days aged manure frozen – 295 Nml/g.VS, 73 % CH_4 and 20 % CO_2
- 40 days aged manure not frozen – 214 Nml/g.VS, 67 % CH_4 and 27 % CO_2

The frozen manure samples indicate that an average of 240 Nml/g.VS of biogas can be produced when the manure is less than 40 days old and treated with the same process parameters. With an average methane and carbon dioxide percentage of 63 % and 31 % respectively. The accumulated biogas volume of the rumen samples as well as the accumulated methane and carbon dioxide percentages was measured as follows:

- Rumen for fresh manure not frozen – 35 Nml, 65 % CH_4 and 29 % CO_2
- Rumen for all frozen samples – 31 Nml, 61 % CH_4 and 33 % CO_2
- Rumen for 40 days aged manure not frozen – 116 Nml, 78 % CH_4 and 16 % CO_2

The kinetics of biogas production rate was compared to the Gompertz equation. The experimentally determined rate of biogas production correlated closely to the Gompertz equation rate of biogas production. The correlation coefficient between the experimentally determined biogas production rate and the Gompertz equation of biogas production rate ranges between 0.98 and 0.99 for all the differently aged manure samples.

The secondary objective of this study was to investigate a techno-economic model through the design and economics of a biogas plant in South Africa. The design of the biogas plant was based on 7 000 cattle that would produce 58 330 kg manure per day. The average biogas yield of 240 Nm^3/ton.VS was assumed for calculation illustration, together with the average TS and VS content of 17% and 80% (as a % of TS) respectively as it was experimentally determined. The designed total power yield of the biogas plant was 555.3 kW for the CHP. The electrical power of 166.6 kW would be produced from a 220 kW engine and the heat energy produced was

277.7 kW. The total electrical and heat power consumption of the biogas plant was designed to be 5.0 kW and 90.7 kW respectively.

The economic viability of the biogas plant was based on a proposed REFIT value of US$ 0.0926 (R1.39) per kWh for the sales of electrical energy generated from biogas. The annual capital, consumption and operational costs of the biogas plant was calculated to be US$ 33 200, US$ 16 617 and US$ 16 209 respectively. The total annual income and costs of the biogas plant was US$ 140 133 and US$ 66 026 respectively. This leads to an annual revenue of US$ 74 107 for the biogas plant. The ROI = 30.6% (> 13%) and is attractive from the commercial point of view and will enter the economic potential. The NPV, IRR and PBT was calculated to be US$ 542 792, 30.4 % and 3.3 years respectively. The ROI, NPV, IRR and PBT was the tools used to determine the economic viability of the different manure samples. The weight loss during drying as well as the loss in TS and VS had an impact on the biogas volume produced and in turn the economic viability of each individual sample.

The comparison of the different manure samples showed that the drying process played an important role in the economic viability of the biogas plant. The weight loss of the manure samples during the drying process caused variations in TS and VS which affected the biogas yield and quality. Thus the economic viability of the biogas plant was dependent on the TS, VS and biogas production that was affected by the drying process. The results showed that the biogas plant viability would depend on a certain drying time for its economic viability. The 11 F and 40 NF manure samples were less economical due to the low income from electrical sales caused by changes in TS, VS and biogas production. The economic study was focused on the sales of electric energy and digestate as fertiliser, thus the annual revenue of the biogas plant can be increased if the heat energy can be sold or utilised further. Thus the economic viability of the biogas plant is dependent on the sales of electric and heat energy (utilizing more heat energy) as well as the sales of digestate as fertiliser.

7.3 Recommendations

The key variables in determining the amount of biogas that can be produced from cattle manure in South Africa were identified. Through the results obtained from the BMP test it was clear that not much VS were loss in the aging process. The loss of water was found to be more significant than the loss of VS during the aging process. The BMP test showed that that the amount of biogas formed was significant enough to evaluate the possibility of building an agricultural biogas plant. The design of an agricultural biogas plant and its economic viability gave rise to the amount of power and revenue that can be generated. Thus there is room to further develop the biogas field in South Africa to produce electricity from waste products such as cattle manure.
Recommendations for investors and companies for considering to establish a biogas plant:

- Do a thorough investigation of how much biogas the feedstock would produce and determine the cost and revenue that will transpire when establishing a biogas plant.
- Continue with further research on other feedstock that is abundant in South Africa that can potentially produce biogas.
- Ensure that the biogas plant is operated under the correct conditions that will favour economic biogas production.
- Commit the construction of a biogas plant towards environmental sustainability through renewable energy sources that are freely available.
- Through environmental sustainable renewable energy a new REFIT value can be negotiated with government and large companies that are committed in generating sustainable and environmentally friendly electricity.
- Consider merging other renewable energy technologies such as PV and CSP with the biogas plant to generate more electricity and to make the plant more cost effective.

7.4 Suggestions for future research

Renewable energy is a field that is rapidly growing in South Africa due to the high demand for electricity and low capacity to generate it. The field of generating electricity from biogas is lacking behind in South Africa when compared to European countries. The field of generating biogas from waste feedstock that is abundant in South Africa needs to be researched and developed further. There is a need for other researchers to investigate other feedstocks and the AD process and to produce biogas more efficiently.

The following are some recommendations that future researches can focus on more thoroughly:

- The AD process parameters such as temperature, pH levels and mixing intensities can be investigated on a large scale to evaluate the biogas production.
- The co-digestion of other freely available feedstocks can be investigated for maximum biogas production.
- Future studies can also include the impact that biogas production has on reducing global warming through emitting less harmful carbon dioxide.
- Further studies must be done on the feedstock to determine the exact nutrition of the feedstock that produces the biogas and the bacterial population that is responsible for it.

7.5 Evaluation of the study

The primary objective of this study was to assess the biogas yield from cattle manure in South Africa. The difference in biogas yield and quality was assessed for manure that ranged from fresh to manure that was periodically aged to 40 days. The BMP results that are portrayed in Chapter 5 outline the results of the amount of biogas that was produced by each type of manure. The secondary objective of the study was to investigate a techno-economic viability study in terms of the design and economics of a biogas plant in South Africa.

The introduction in Chapter 1 gave a broad overview of the background and objectives of the study. Through the theoretical foundation in Chapter 2 and the literature study in Chapter 3 a good understanding of AD was developed. This gave rise to a clear understanding of AD to develop a methodology in Chapter 4. The results that were obtained through the BMP test was brought forward in Chapter 5. Thus from the findings in Chapter 6 it can be concluded that a biogas plant is economically viable.

7.6 Conclusion

This study was aimed at the biogas yield from cattle manure and to develop a techno-economic model and its viability in South Africa. In determining the amount of biogas that can be produced from cattle manure the viability of a biogas plant was evaluated. Thus based on the assumptions made and the data gathered it was concluded that a biogas plant is economically viable and would generate electricity and heat.

The contribution of this study towards renewable energy is significant due to the viability of constructing a biogas plant in South Africa. The study highlighted the drying process of manure, the biogas yield and quality, the design and economic viability of a biogas plant. The study was focused on the biogas yield from differently aged cattle manure in order to investigate the viability of a biogas plant. Through the biogas yield the design and economic viability of the biogas plant was established. This study can be used as a guideline for future biogas plant designers as it gives an insight on the biogas yield from cattle manure.

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Appendix A: Detailed figures of biogas production over 41 days

Figure 16 shows the accumulated gas formation for fresh manure that was not frozen. The accumulated biogas that was generated over the 41 day period was measured to be 205 Nml/g.VS and the corresponding methane and carbon dioxide volumes were measured to be 124 Nml/g.VS and 67 Nml/g.VS respectively. The fresh manure that was not frozen was used as a baseline graph to which all other gas formation was measured against. The graphs that follows was measured against figure 10 for performance in terms of accumulated biogas, methane and carbon dioxide volume formation.

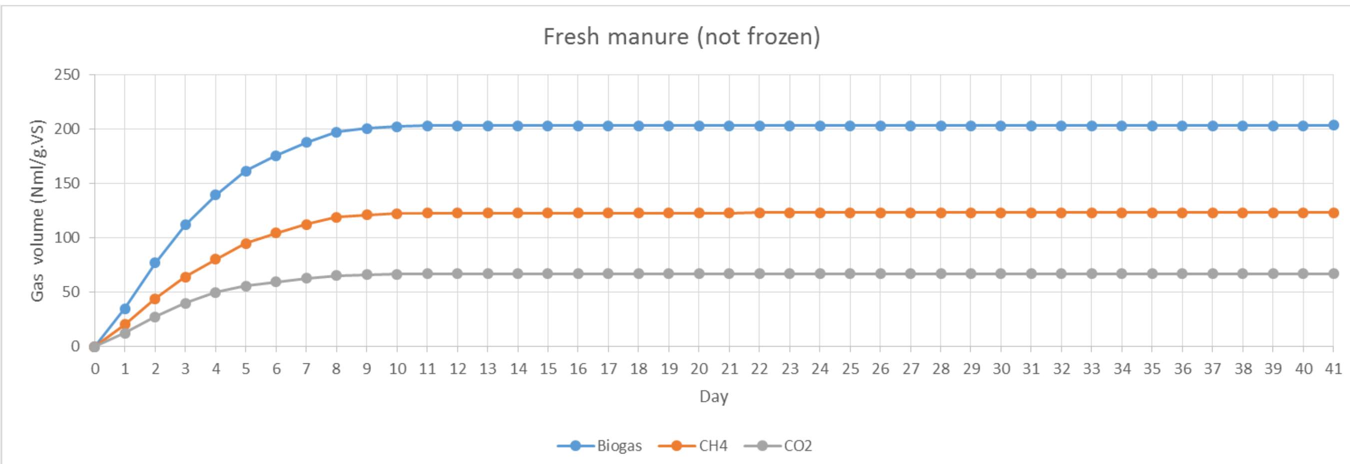

Figure 16: Accumulated gas formation for fresh manure that was not frozen

Figure 17 shows the accumulated gas formation for fresh manure that was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 217, 140 and 63 Nml/g.VS respectively. This sample generated 13 Nml/g.VS more biogas, 16 Nml/g.VS more methane and 4 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 65 % methane and 29 % carbon dioxide.

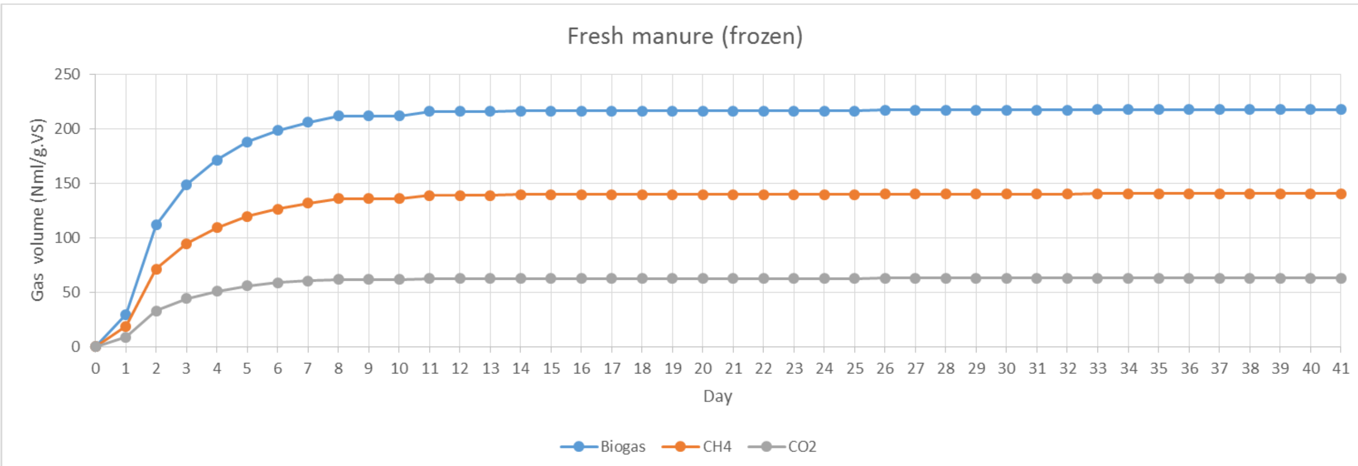

Figure 17: Accumulated gas formation for fresh manure that was froze

Figure 18 shows the accumulated gas formation for manure that was aged for 4 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 206, 129 and 64 Nml/g.VS respectively. This sample generated 2 Nml/g.VS more biogas, 5 Nml/g.VS more methane and 3 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 63 % methane and 31 % carbon dioxide.

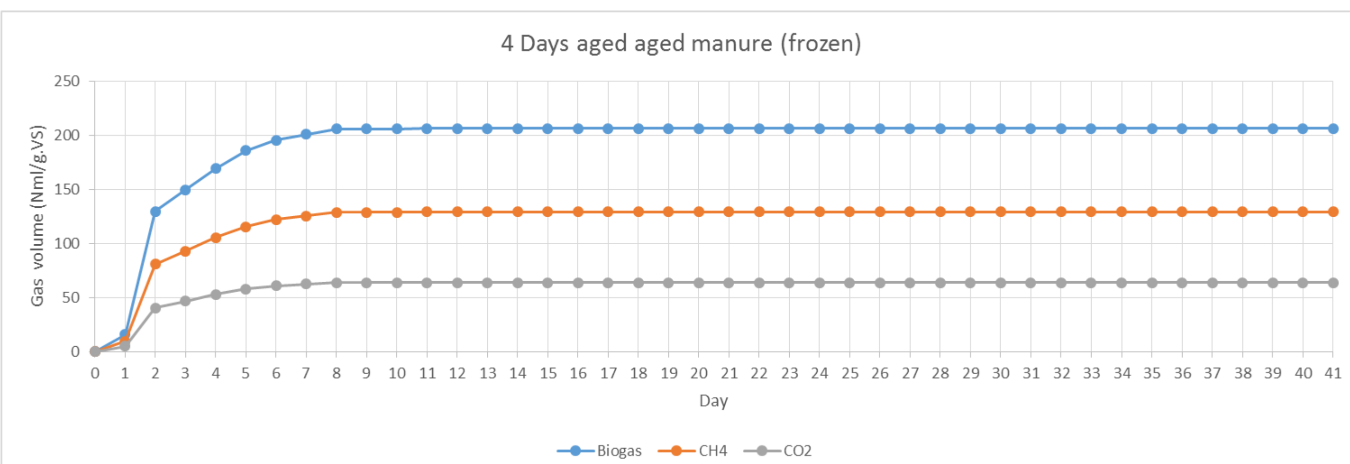

Figure 18: Accumulated gas formation for manure that was aged for 4 days and frozen

Figure 19 shows the accumulated gas formation for manure that was aged for 7 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 199, 115 and 71 Nml/g.VS respectively. This sample generated 6 Nml/g.VS less biogas, 9 Nml/g.VS less methane and 4 Nml/g.VS more carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 58 % methane and 36 % carbon dioxide.

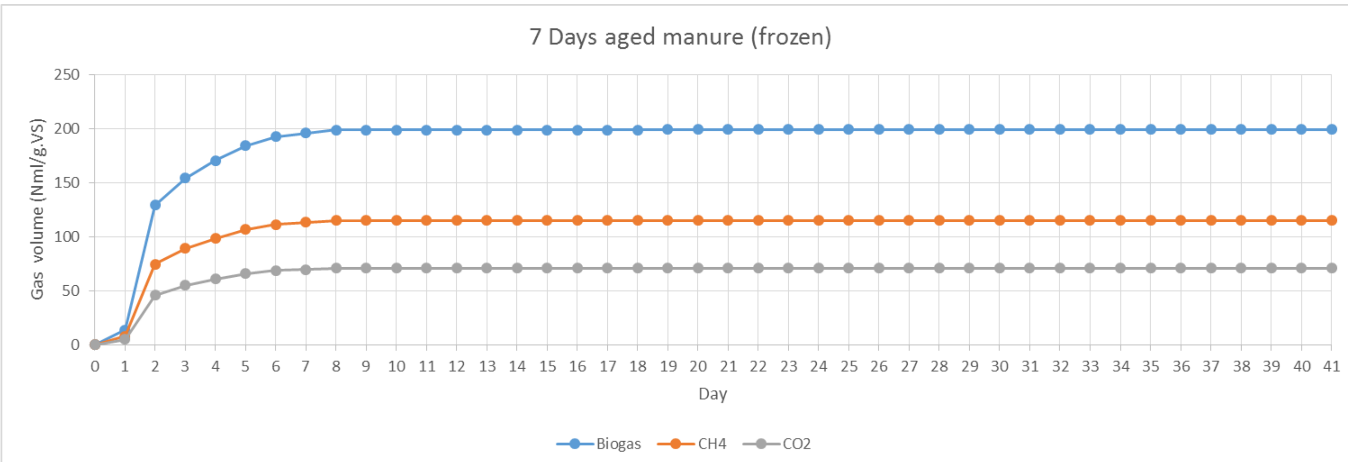

Figure 19: Accumulated gas formation for manure that was aged for 7 days and frozen

Figure 20 shows the accumulated gas formation for manure that was aged for 11 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 154, 90 and 54 Nml/g.VS respectively. This sample generated 50 Nml/g.VS less biogas, 33 Nml/g.VS less methane and 14 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 59 % methane and 35 % carbon dioxide.

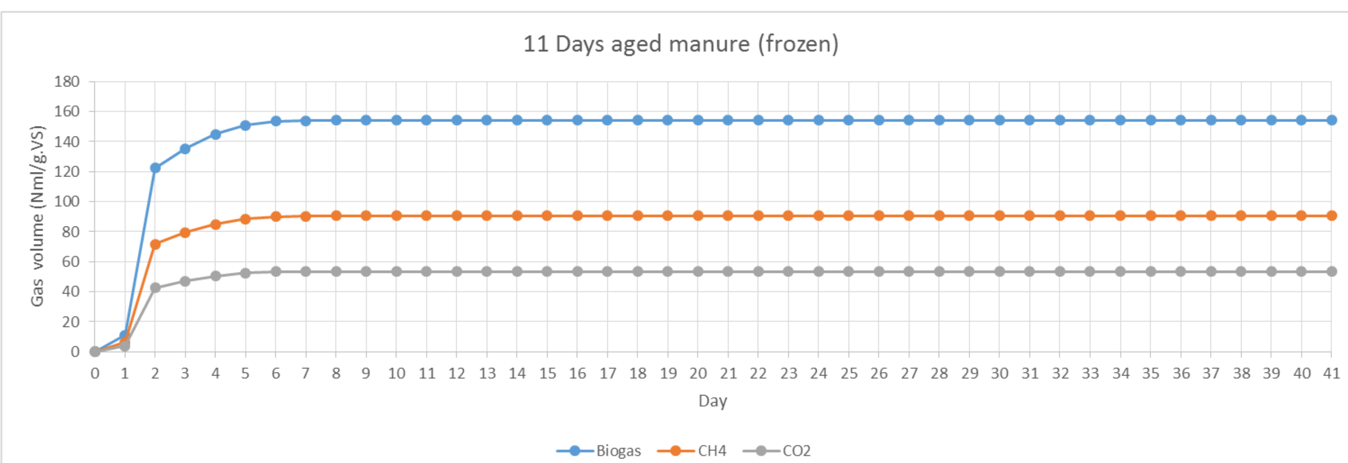

Figure 20: Accumulated gas formation for manure that was aged for 11 days and frozen

Figure 21 shows the accumulated gas formation for manure that was aged for 14 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 208, 106 and 88 Nml/g.VS respectively. This sample generated 3 Nml/g.VS more biogas, 18 Nml/g.VS less methane and 21 Nml/g.VS more carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 51 % methane and 42 % carbon dioxide.

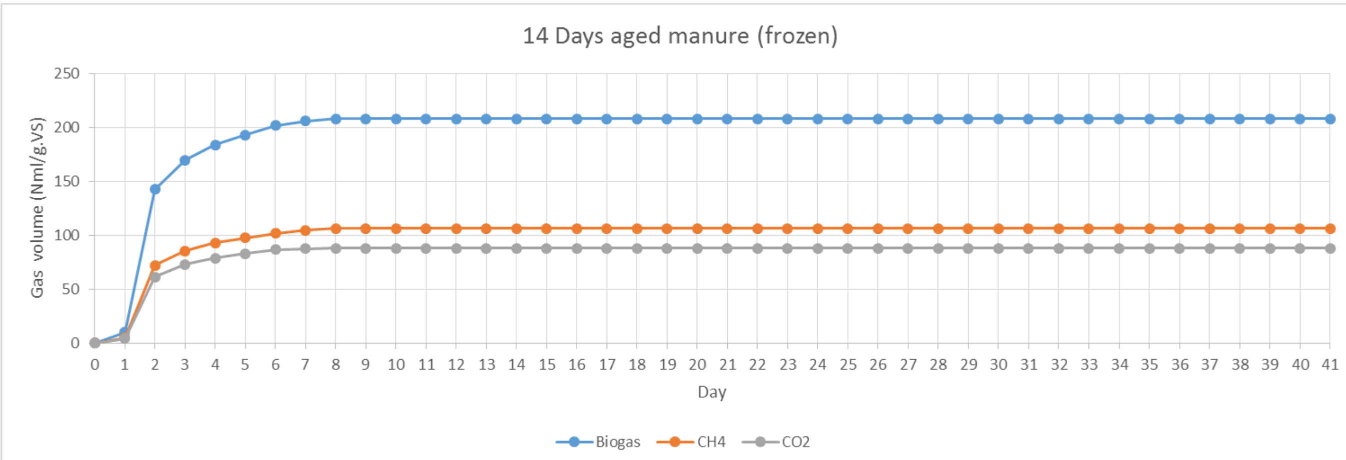

Figure 21: Accumulated gas formation for manure that was aged for 14 days and frozen

Figure 22 shows the accumulated gas formation for manure that was aged for 21 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 208, 116 and 78 Nml/g.VS respectively. This sample generated 4 Nml/g.VS more biogas, 7 Nml/g.VS less methane and 11 Nml/g.VS more carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 56 % methane and 37 % carbon dioxide.

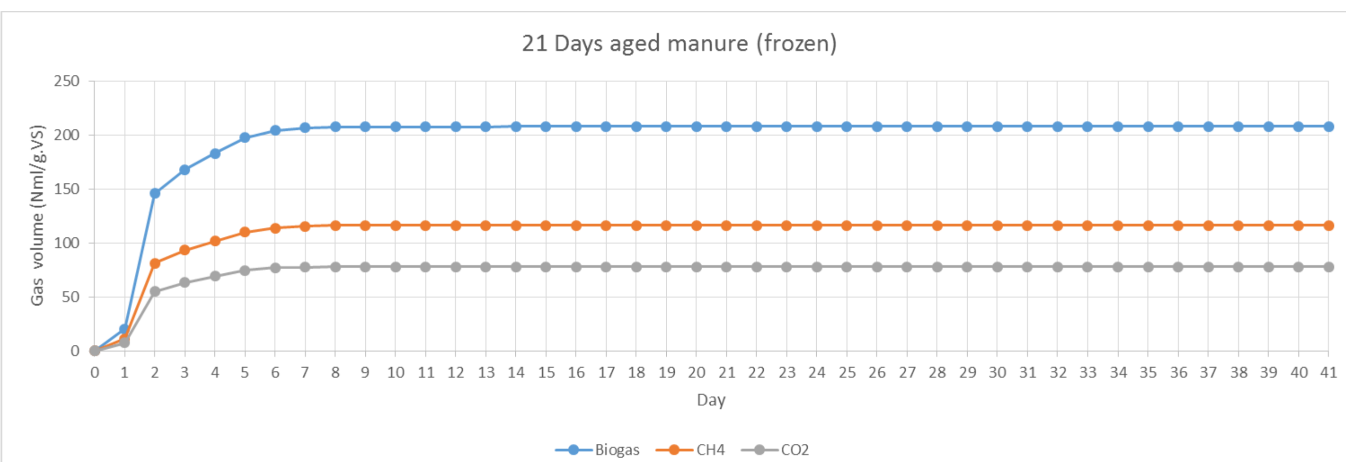

Figure 22: Accumulated gas formation for manure that was aged for 21 days and frozen

Figure 23 shows the accumulated gas formation for manure that was aged for 28 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 245, 173 and 56 Nml/g.VS respectively. This sample generated 40 Nml/g.VS more biogas, 49 Nml/g.VS more methane and 11 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 71 % methane and 23 % carbon dioxide.

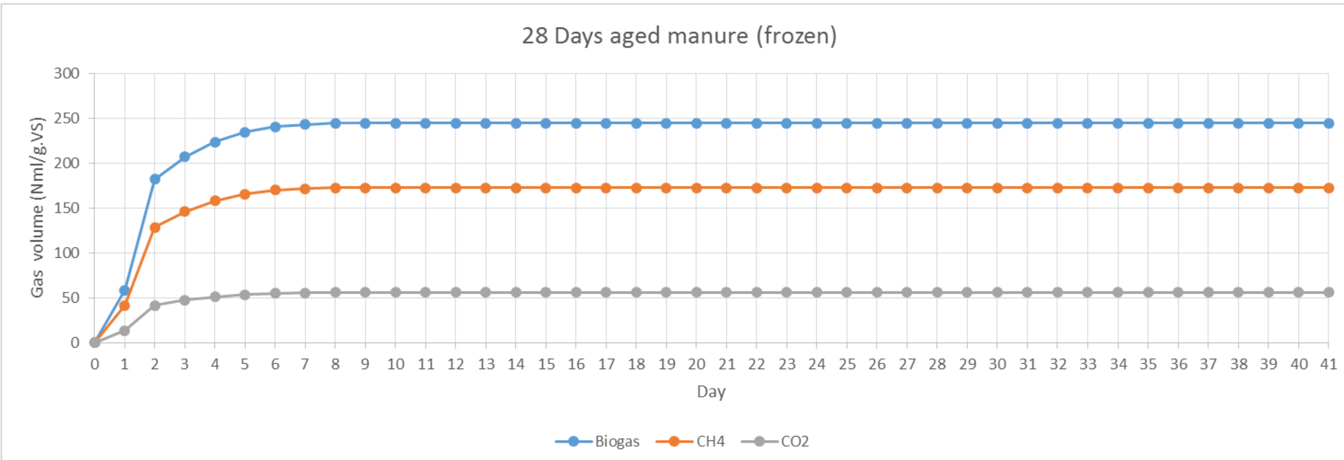

Figure 23: Accumulated gas formation for manure that was aged for 28 days and frozen

Figure 24 shows the accumulated gas formation for manure that was aged for 35 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 369, 262 and 83 Nml/g.VS respectively. This sample generated 164 Nml/g.VS more biogas, 138 Nml/g.VS more methane and 16 Nml/g.VS more carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 71 % methane and 22 % carbon dioxide.

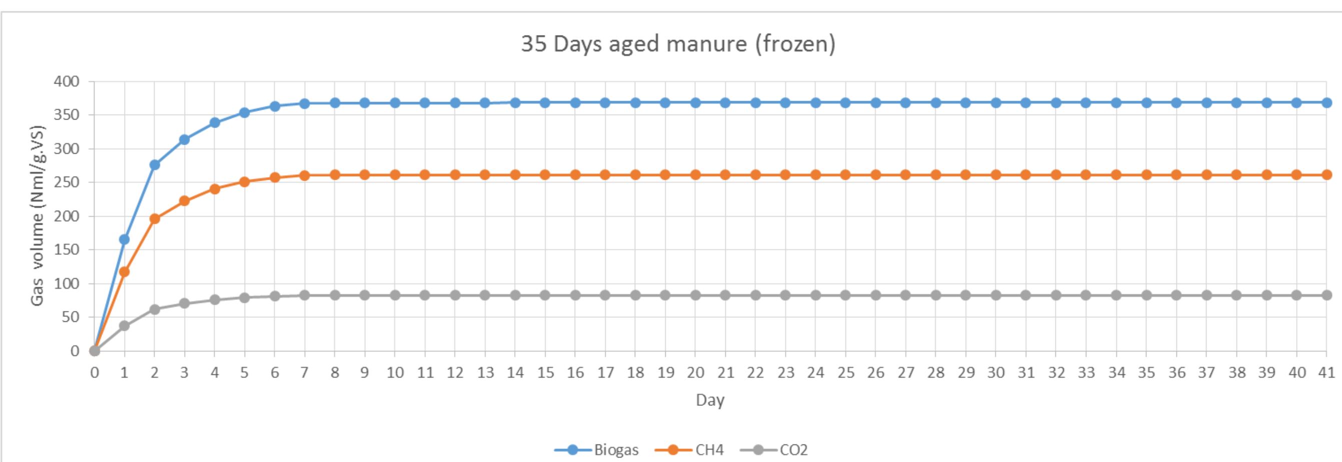

Figure 24: Accumulated gas formation for manure that was aged for 35 days and frozen

Figure 25 shows the accumulated gas formation for manure that was aged for 40 days and was frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 295, 217 and 59 Nml/g.VS respectively. This sample generated 91 Nml/g.VS more biogas, 93 Nml/g.VS more methane and 8 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 73 % methane and 20 % carbon dioxide.

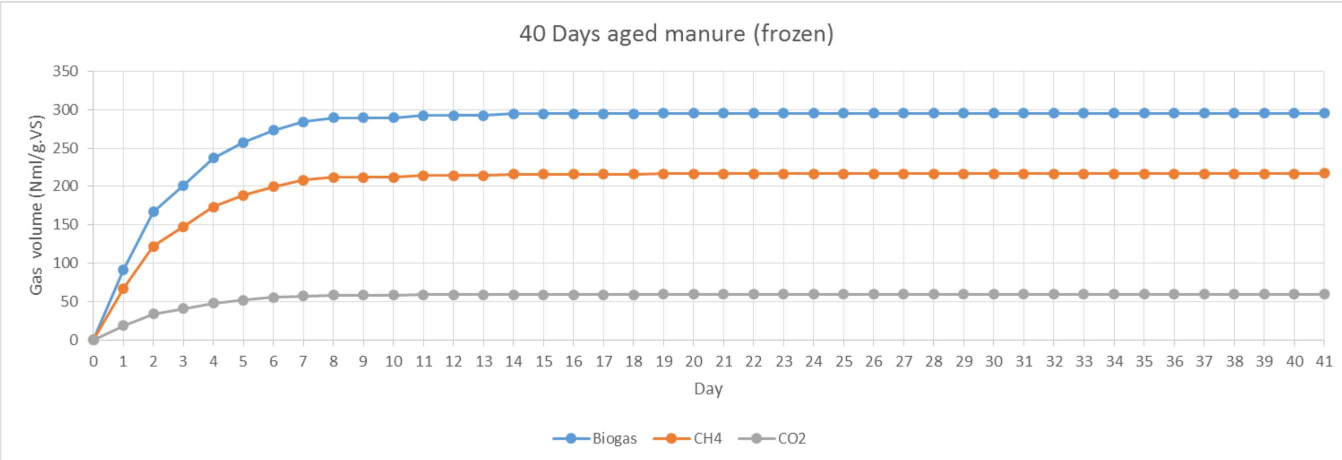

Figure 25: Accumulated gas formation for manure that was aged for 40 days and frozen

Figure 26 shows the accumulated gas formation for manure that was aged for 40 days and was not frozen. The accumulated biogas, methane and carbon dioxide that was generated from this sample of manure was measured to be 214, 143 and 57 Nml/g.VS respectively. This sample generated 10 Nml/g.VS more biogas, 19 Nml/g.VS more methane and 10 Nml/g.VS less carbon dioxide than the fresh unfrozen manure sample. The total accumulated biogas sample was made up of 67 % methane and 27 % carbon dioxide.

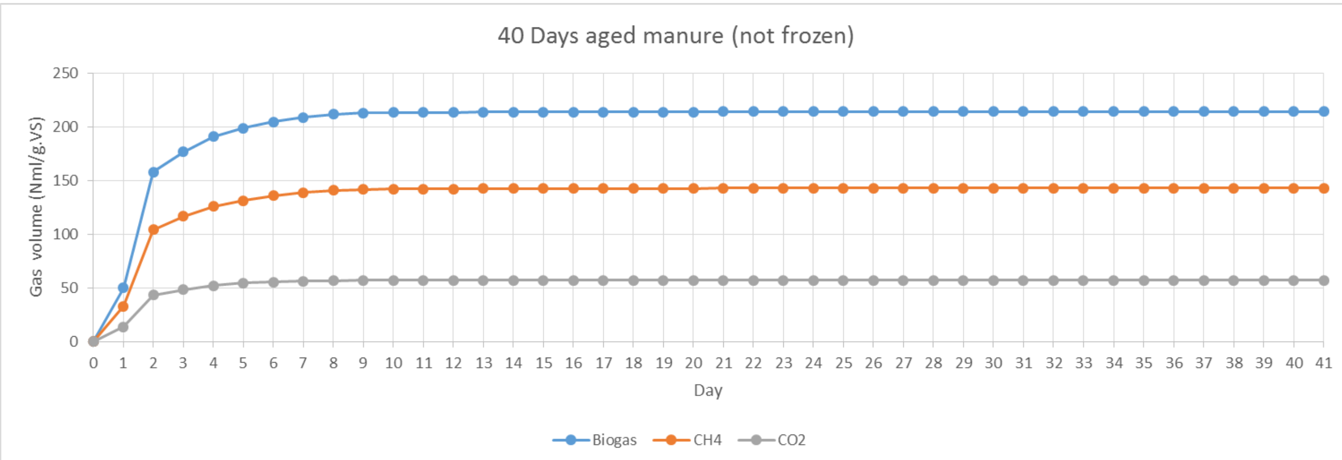

Figure 26: Accumulated gas formation for manure that was aged for 40 days and not frozen

Figure 27 shows the accumulated gas formation of the rumen that was used to populate the fresh unfrozen manure sample with anaerobic bacteria. The accumulated biogas, methane and carbon dioxide that was generated from this sample of rumen was measured to be 35, 22 and 10 Nml respectively. The total accumulated biogas sample was made up of 65 % methane and 29 % carbon dioxide.

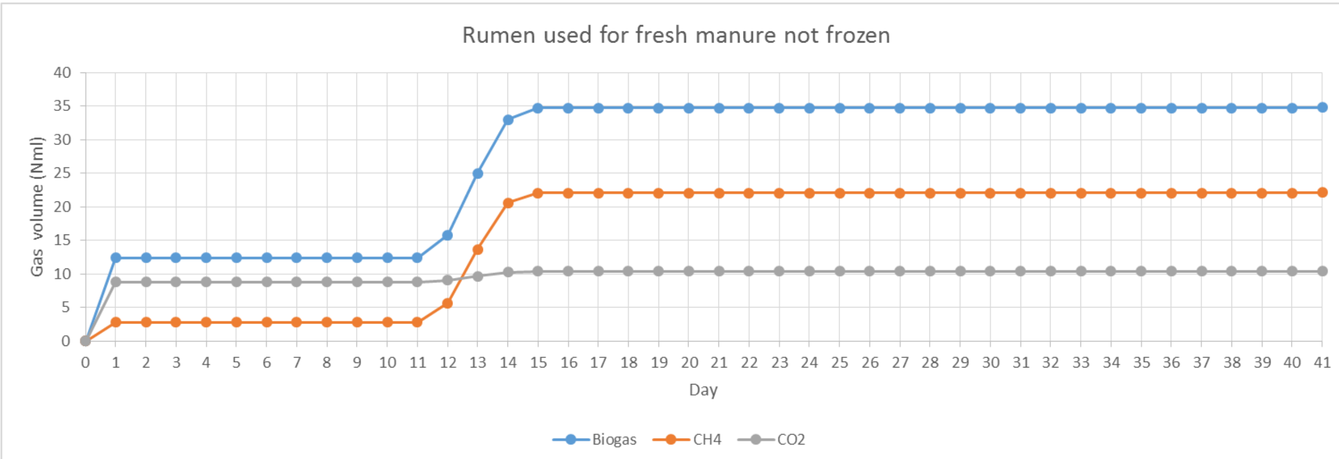

Figure 27: Accumulated gas formation of rumen used for fresh manure not frozen

Figure 28 shows the accumulated gas formation of the rumen that was used to populate all the frozen manure samples with anaerobic bacteria. The accumulated biogas, methane and carbon dioxide that was generated from this sample of rumen was measured to be 31, 19 and 10 Nml respectively. The total accumulated biogas sample was made up of 61 % methane and 33 % carbon dioxide.

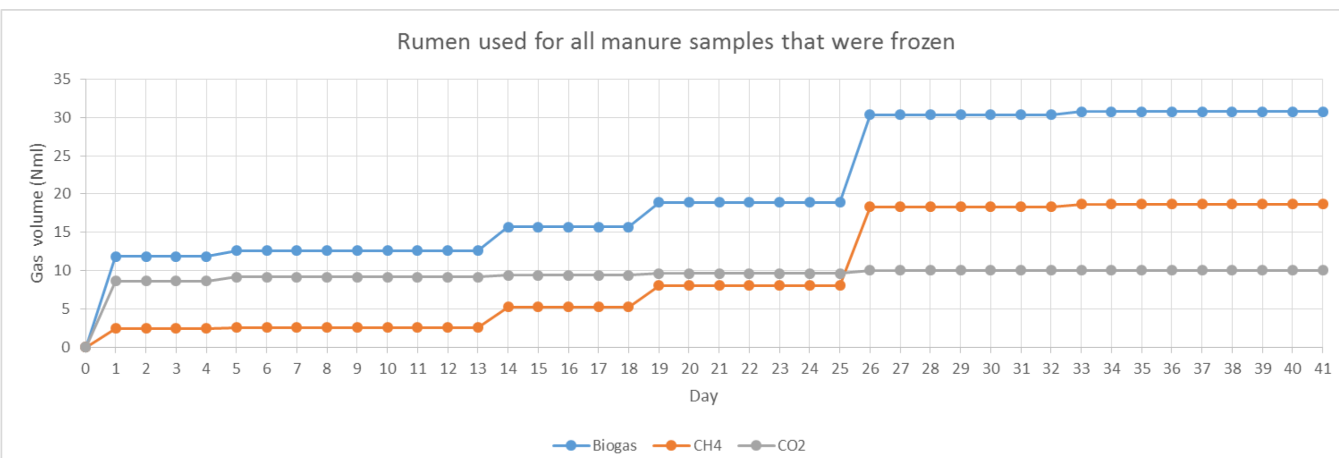

Figure 28: Accumulated gas formation of rumen used for all manure samples that were frozen

Figure 29 shows the accumulated gas formation of the rumen that was used to populate the 40 days aged manure sample that was not frozen with anaerobic bacteria. The accumulated biogas, methane and carbon dioxide that was generated from this sample of rumen was measured to be 116, 90 and 18 Nml respectively. The total accumulated biogas sample was made up of 78 % methane and 16 % carbon dioxide.

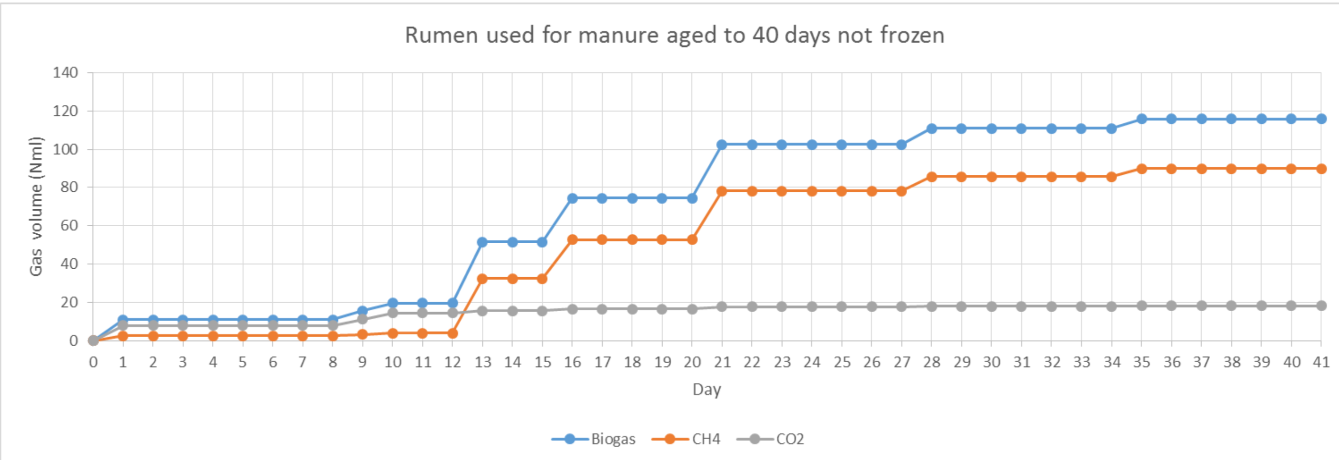

Figure 29: Accumulated gas formation of rumen used for manure aged to 40 days not frozen

Appendix B: Detailed figures of percentage methane and carbon dioxide and the volume of biogas over 41 days

Figure 30 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the fresh manure sample that was not frozen. The biogas volume that was produced on day 1, 5, 12 and 26 was measured to be 35.3, 22.2, 0.2 and 0.0 Nml/g.VS respectively. On day 1, 5, 12 and 26 the corresponding methane percentage was measured to be 58, 67, 70 and 81 % and the corresponding carbon dioxide percentage was measured to be 36, 26, 23 and 12 % respectively.

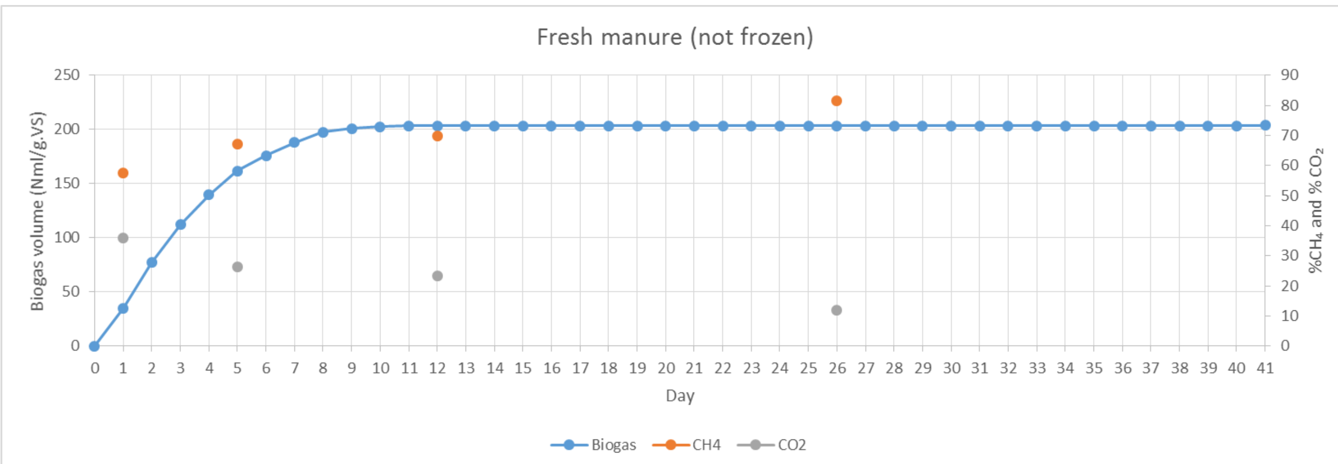

Figure 30: Biogas volume and $\%CH_4$ and $\%CO_2$ for fresh manure not frozen

Figure 31 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the fresh manure sample that was frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 22.7, 7.5, 3.9, 0.8, 0.0 and 0.6 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 64, 71, 76, 78, 82 and 82 % and the corresponding carbon dioxide percentage was measured to be 30, 23, 17, 16, 11 and 11 % respectively.

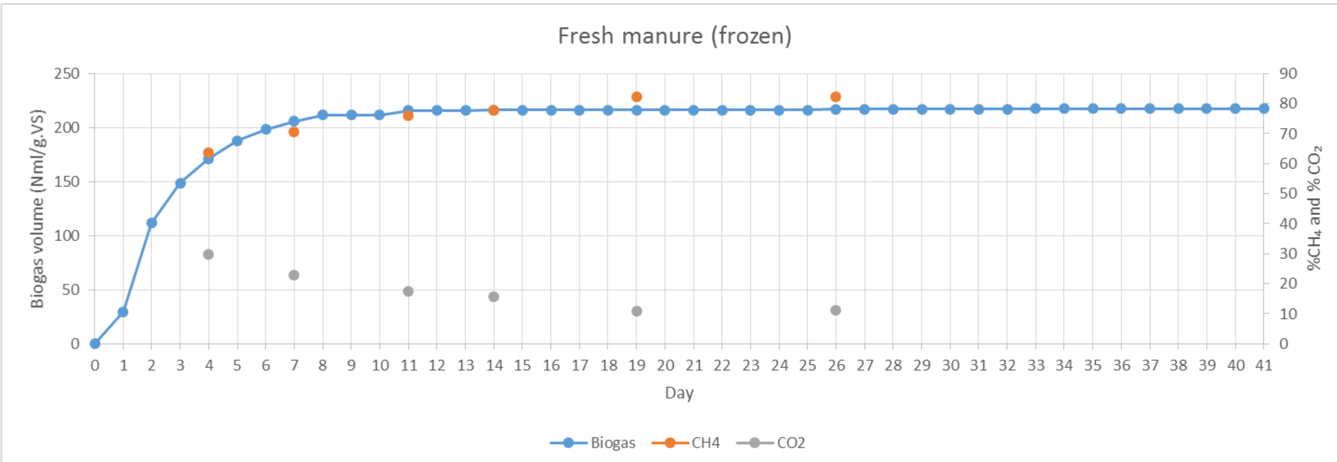

Figure 31: Biogas volume and $\%CH_4$ and $\%CO_2$ for fresh manure that was frozen

Figure 32 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 4 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 19.7, 5.4, 0.3, 0.0, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 62, 66, 74, 77, 83 and 83 % and the corresponding carbon dioxide percentage was measured to be 31, 28, 19, 17, 10 and 11 % respectively.

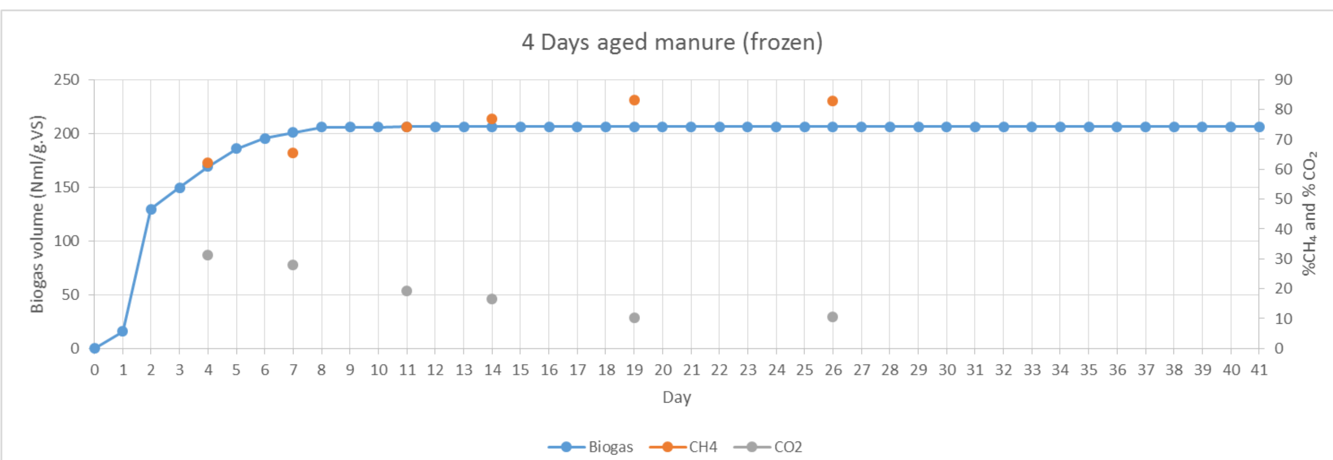

Figure 32: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 4 days and frozen

Figure 33 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 7 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 16.0, 3.5, 0.0, 0.0, 0.2, and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 58, 61, 71, 74, 82 and 83 % and the corresponding carbon dioxide percentage was measured to be 36, 33, 22, 20, 11 and 10 % respectively.

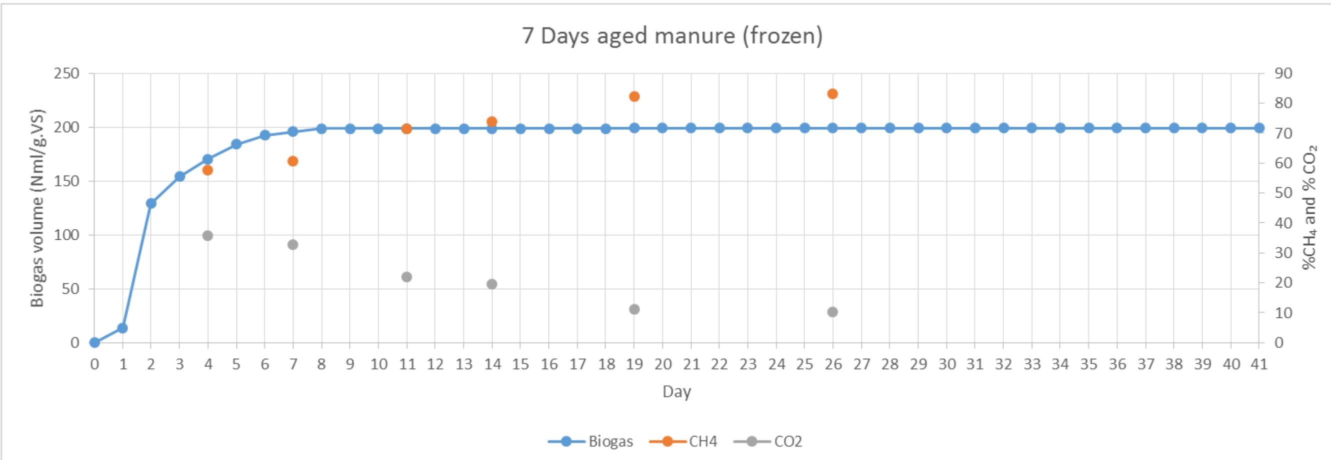

Figure 33: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 7 days and frozen

Figure 34 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 11 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 9.4, 0.3, 0.0, 0.0, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 59, 68, 75, 78, 84 and 81 % and the corresponding carbon dioxide percentage was measured to be 35, 25, 19, 15, 9 and 12 % respectively.

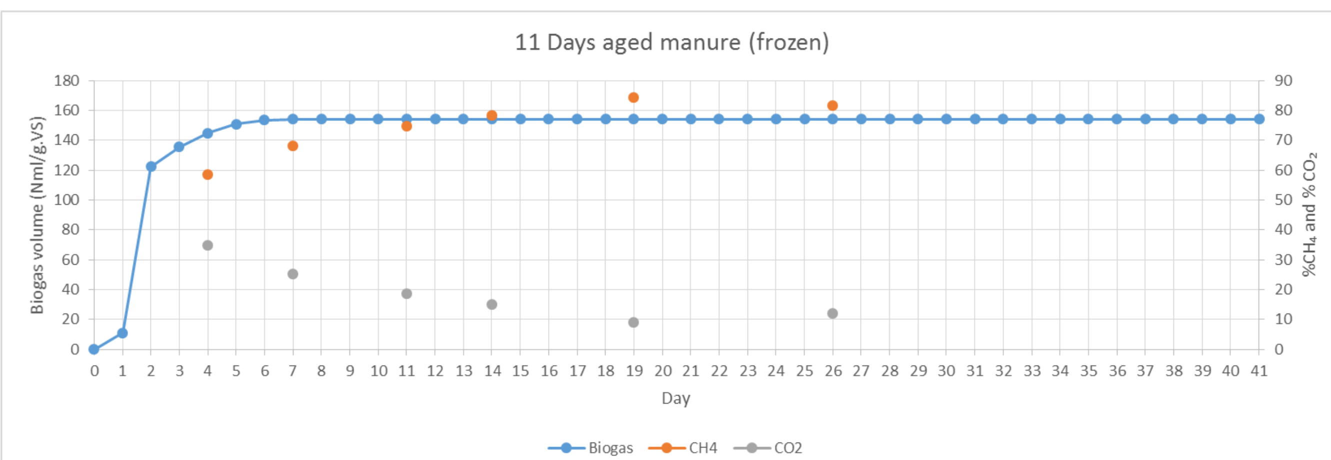

Figure 34: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 11 days and frozen

Figure 35 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 14 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 14.2, 4.2, 0.0, 0.0, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 51, 69, 71, 75, 80 and 82 % and the corresponding carbon dioxide percentage was measured to be 43, 24, 22, 18, 13 and 11 % respectively.

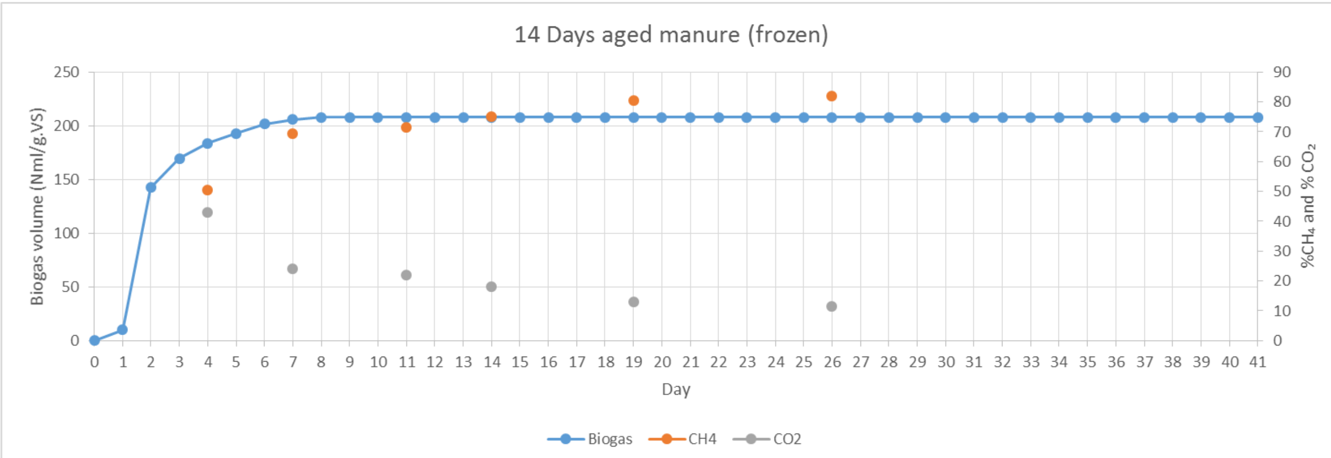

Figure 35: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 14 days and frozen

Figure 36 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 21 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 15.0, 2.4, 0.0, 0.4, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 56, 72, 76, 77, 81 and 81 % and the corresponding carbon dioxide percentage was measured to be 38, 22, 18, 16, 13 and 12 % respectively.

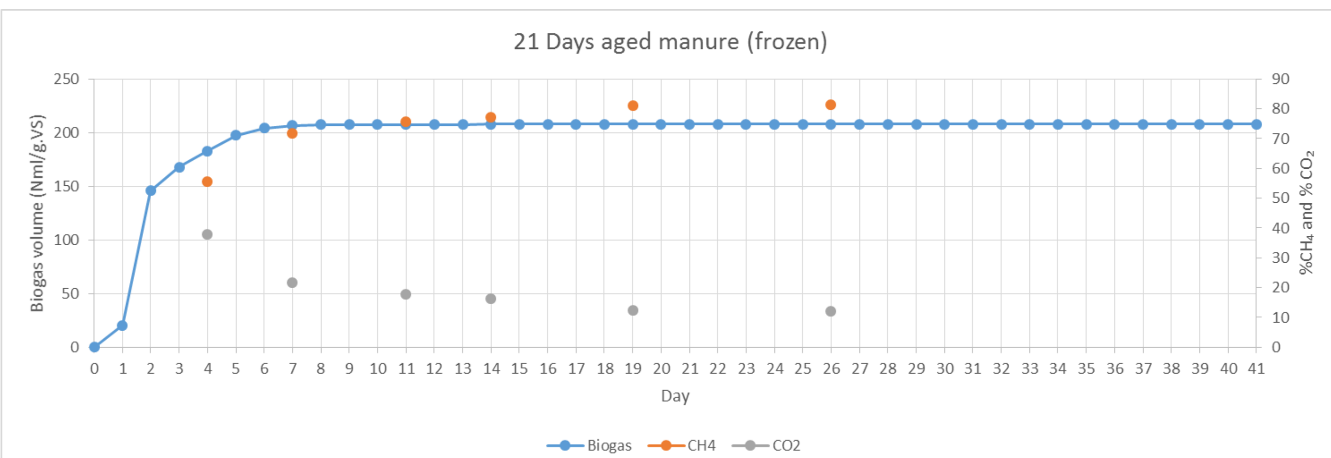

Figure 36: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 21 days and frozen

Figure 37 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 28 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 16.9, 2.5, 0.0, 0.0, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 71, 74, 76, 81, 80 and 81 % and the corresponding carbon dioxide percentage was measured to be 23, 19, 18, 13, 13 and 12 % respectively.

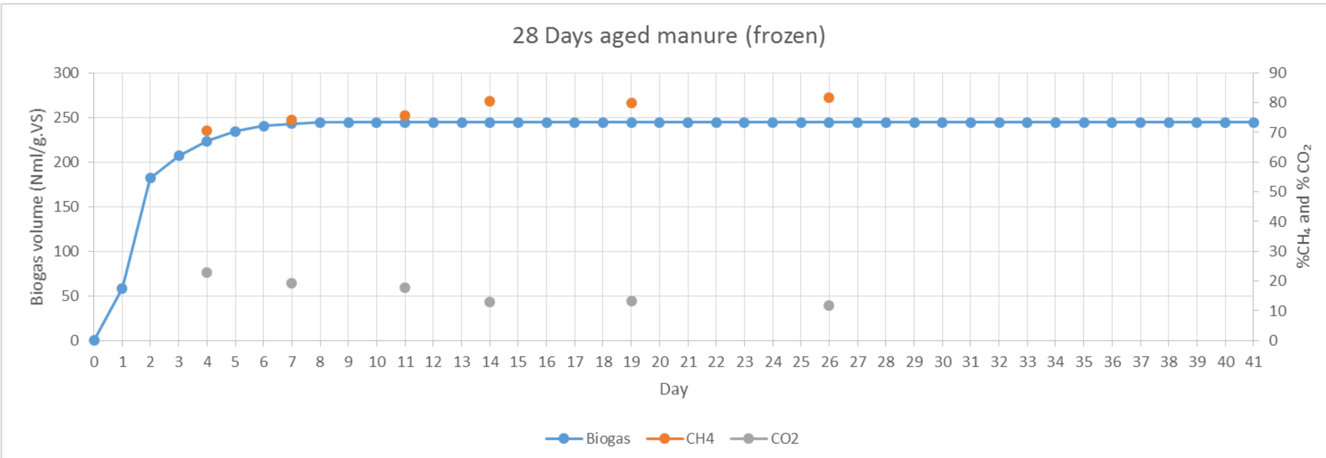

Figure 37: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 28 days and frozen

Figure 38 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 35 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 25.2, 3.9, 0.0, 0.6, 0.0 and 0.0 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 71, 74, 75, 78, 80 and 83 % and the corresponding carbon dioxide percentage was measured to be 23, 19, 18, 16, 13 and 10 % respectively.

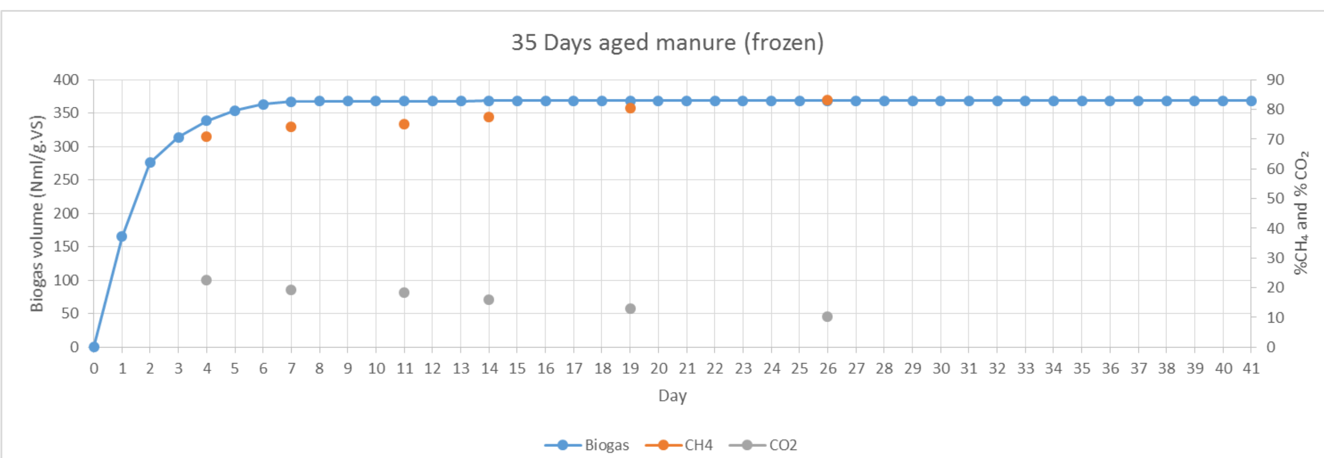

Figure 38: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 35 days and frozen

Figure 39 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 40 days and frozen. The biogas volume that was produced on day 4, 7, 11, 14, 19 and 26 was measured to be 35.6, 11.0, 3.0, 2.4, 0.4 and 0.2 Nml/g.VS respectively. On day 4, 7, 11, 14, 19 and 26 the corresponding methane percentage was measured to be 73, 76, 76, 76, 79 and 81 % and the corresponding carbon dioxide percentage was measured to be 20, 18, 17, 18, 15 and 12 % respectively.

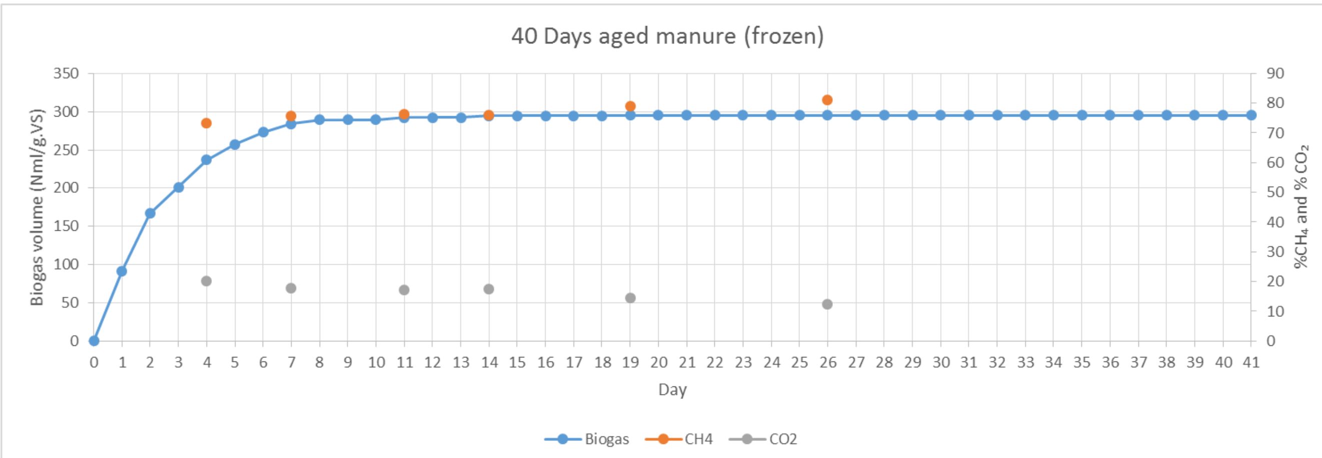

Figure 39: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 40 days and frozen

Figure 40 shows the biogas volume that was produced as well as the methane and carbon dioxide percentages for the manure sample that was aged for 40 days and not frozen. The biogas volume that was produced on day 3, 6, 9, 13, 16, 21 and 28 was measured to be 18.9, 6.1, 1.1, 0.5, 0.0, 0.5 and 0.0 Nml/g.VS respectively. On day 3, 6, 9, 13, 16, 21 and 28 the corresponding methane percentage was measured to be 66, 75, 78, 79, 79, 81 and 83 % and the corresponding carbon dioxide percentage was measured to be 27, 18, 16, 15, 15, 12 and 10 % respectively.

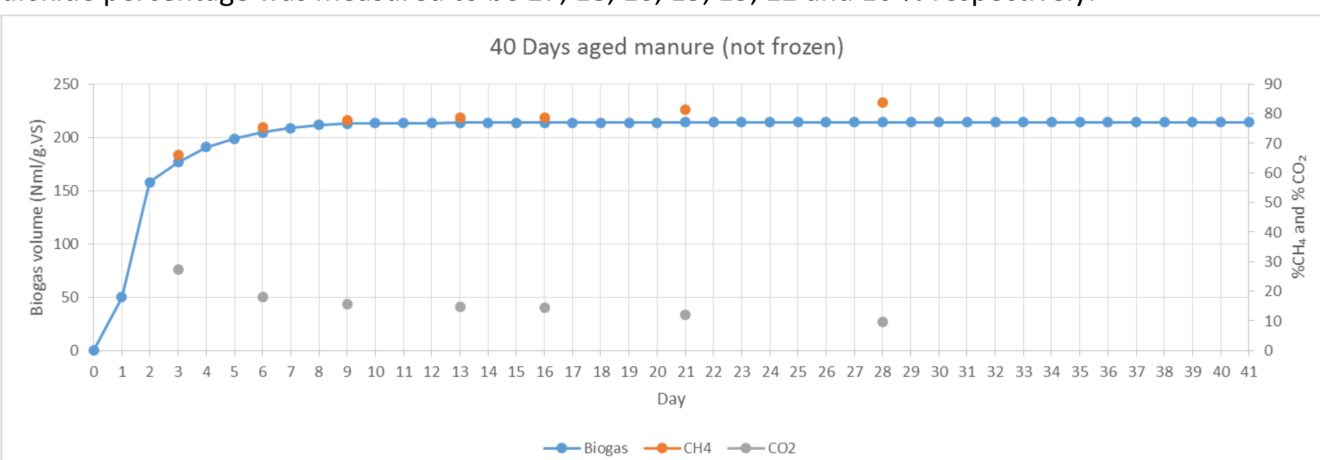

Figure 40: Biogas volume and $\%CH_4$ and $\%CO_2$ for manure that was aged for 40 days and not frozen

Appendix C: List of South African feedlots

Table 15: List of South African feedlots

No.	Name	Location (Province)	Notes
1.	AUSTIN EVANS FEEDLOT	Somerset East (EC)	
2.	ADAM AGRI	Colesberg (NC)	
3.	B. HURWITZ FARMING	Davel (MP)	10 000 Cattle head
4.	BEEFCOR	Bronkhorstspruit (GP)	25 000 Cattle head
5.	BEEFMASTER	Christiana (NW)	20 000 Cattle head
6.	BLOKHUIS FEEDLOT	Harrismith (FS)	
7.	BULL BRAND	Krugersdorp (GP)	40 000 Cattle head
8.	BRAAMS VOERKRALE BK	Durbanville (WC)	4 000 Cattle head
9.	CB FEEDLOT	Reitz (FS)	
10.	CHALMAR BEEF	Wingate Park (GP)	15 000 Cattle head
11.	CLAREMONT FARMING (PTY) LTD	East London (EC)	12 000 Cattle head
12.	DC LOUW FEEDLOT	Adelaide (EC)	
13.	DOORNBULT VOERKRALE (PTY) LTD	Ladanna (L)	
14.	EDLOUIS VOERKRALE (PTY) LTD	Sasolburg (FS)	
15.	FORTRESS BONSMARA	Frankfort (FS)	6 000 Cattle head
16.	JJ FEEDLOT	Vrede (FS)	
17.	KAMEELDRIFT FEEDLOT	Kameeldrift (GP)	8 000 Cattle head
18.	KANHYM ESTATES LTD.	Middelburg (MP)	40 000 Cattle head 12 000 Lamb head
19.	KARAN BEEF	Heidelberg (GP)	120 000 Cattle head
20.	KOODOOLAKE	Stella (NW)	
21.	KELLERMAN BOERDERY	Koringsberg (WC)	
22.	KLEYNFAAN FEEDLOT	Vryheid (KZN)	
23.	KOREM FARM	Karenpark (GP)	
24.	LIEBENBERGSTROOM VOERKRAAL BPK	Edenville (FS)	
25.	MANJOH RANCH	Nigel (GP)	22 000 Cattle head
26.	MALUTI BEEF MEMEL	Memel (FS)	
27.	MADIKOR	Louis Trichardt (L)	
28.	MIKRON BOERDERY	Bultfontein (FS)	
29.	MLEKI'S BEEF	Isando (GP)	
30.	MOORREESBURGSE PRIVATE ABATTOIR AND FEEDLOTS	Moorreesburg (WC)	
31.	MORGAN BEEF	Delmas (MP)	16 000 Cattle head
32.	MUSHLENDOW	Koster (NW)	
33.	MVB FEEDERS	Louis Trichardt (L)	
34.	PIET WARREN PLASE	Gravelotte (L)	

No.	Name	Location (Province)	Notes
35.	POPPIELAND TRUST	Bultfontein (FS)	
36.	RANCH ESTATES	Delmas (MP)	
37.	RHYS EVANS GROUP	Huntersvlei (FS)	3 000 Cattle head
38.	SARDINIA FEEDLOT	Bultfontein (FS)	
39.	SERNICK FEEDLOT	Edenville (FS)	3 000 Cattle head
40.	SIS FARMING	Bethal (MP)	22 000 Cattle head
41.	SKS BOERDERY	Middelburg (MP)	
42.	TANGENI FEEDLOT (PTY) LTD	Dundee (KZN)	
43.	SPARTA BEEF	Marquard (FS)	40 000 Cattle head
44.	TAAIBOSCHBULT (PTY) LTD	Potchefstroom (NW)	
45.	THERON BOERDERY	Pretoria Wes (GP)	
46.	TOMIS SHEEP FEEDLOTS	Riebeeck Kasteel (WC)	10 000 Lamb head
47.	TRIPLE C FEEDLOT	Dundee (KZN)	
48.	VENCOR	Ladanna (L)	
49.	VERCUIEL	Stella (NW)	
50.	VERBREED	Stella (NW)	
51.	VERGEZIGHT	Heilbron (FS)	
52.	WINDHOEK BOERDERY	Pietersburg (L)	

Source: South African Feedlot Association http://www.safeedlot.co.za/index.asp
– Cited 20 April 2016

South African Provinces:

- EC = Eastern Cape
- NC = Northern Cape
- MP = Mpumalanga
- GP = Gauteng Province
- NW = North West Province
- FS= Free State
- WC = Western Cape
- L = Limpopo
- KZN = KwaZulu-Natal

Appendix D: Manure sample preparation and stack height of samples

Table 16: Manure sample drying schedule

Stack height	**0**	**4**	**7**	**11**	**14**	**21**	**28**	**35**	**40**
50 mm		water loss	water loss	water loss	water loss	water loss	water loss	water loss	water loss
		Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front
		water loss	water loss	water loss	water loss	water loss	water loss	water loss	water loss
100mm		Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front
	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**	Freeze, **AD**
	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP	TS,VS,CP
150mm		water loss	water loss	water loss	water loss	water loss	water loss	water loss	water loss
		Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front
	not freeze, **AD**								not freeze, **AD**
		water loss	water loss	water loss	water loss	water loss	water loss	water loss	water loss
200mm		Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front
		water loss	water loss	water loss	water loss	water loss	water loss	water loss	water loss
250mm		Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front	Dry front

Appendix E: Pictures of manure drying and experimental setup

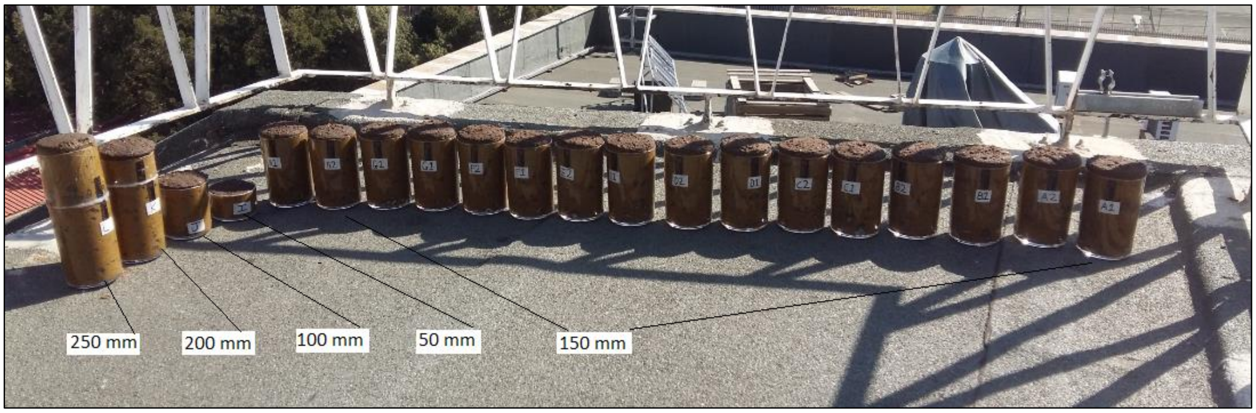

Figure 41: Manure sampling containers

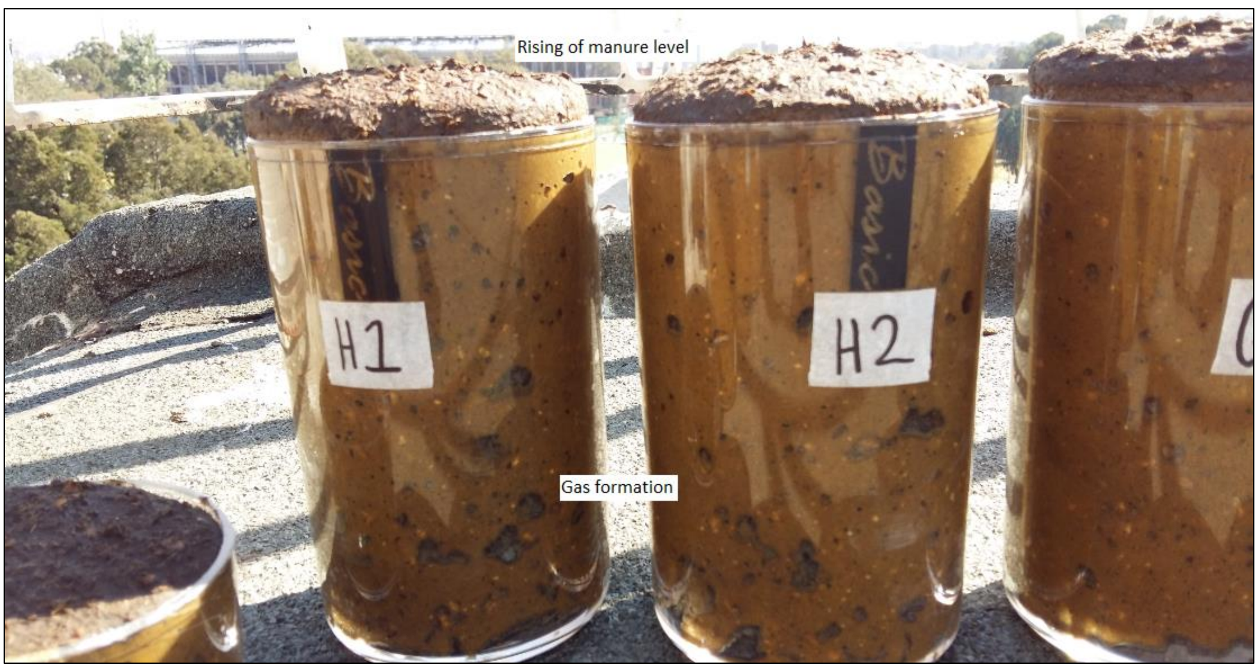

Figure 42: Gas formation in manure causing the manure level to rise up

Figure 43: Fresh manure before aging

Figure 44: Manure aged for 40 days containing wet and dry parts

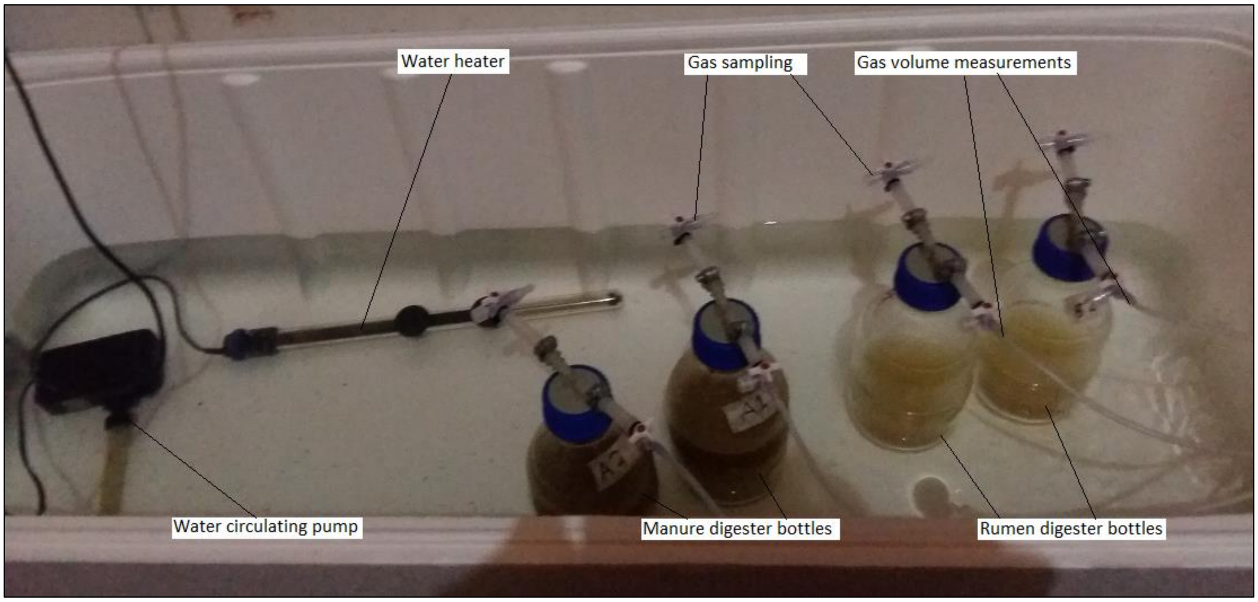

Figure 45: Water bath and its components

Figure 46: Water bath containing all 28 digester bottles

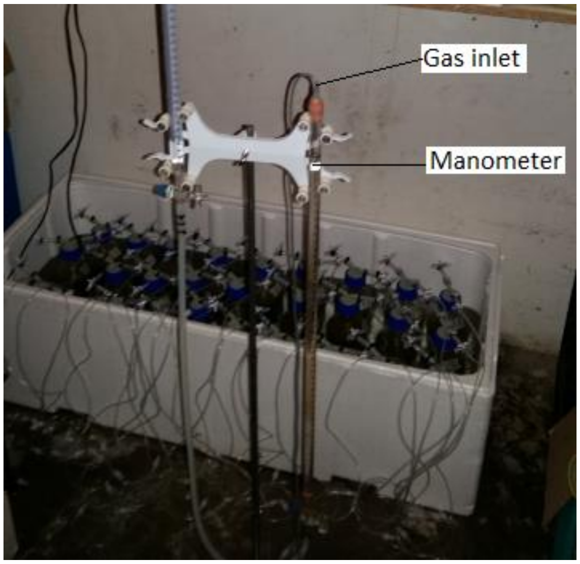

Figure 47: Manometer to measure biogas volume

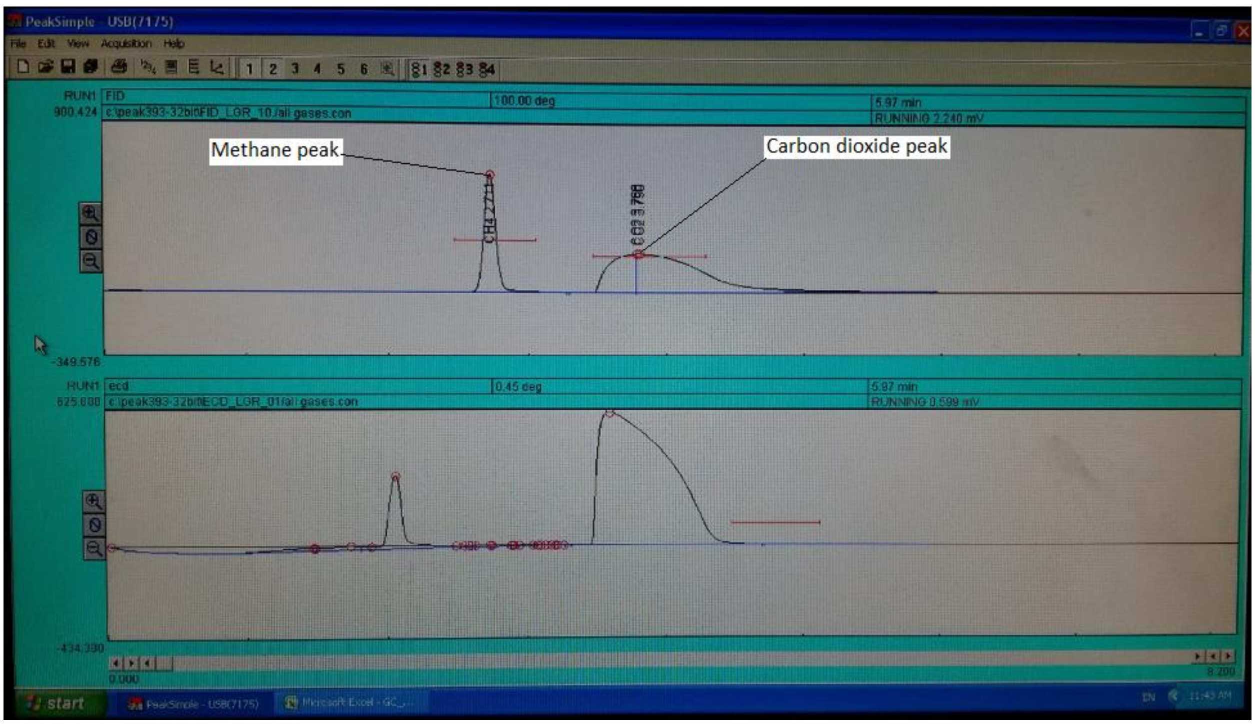

Figure 48: Screenshot of PeakSimple used to measure methane and carbon dioxide content