DESIGN OF AN ANAEROBIC BIODIGESTION SYSTEM UTILISING THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE FOR BIOGAS PRODUCTION IN AN URBAN ENVIRONMENT

by

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DECLARATION

I, the undersigned, hereby declare that this dissertation, which I herewith submit for the research qualification

MASTERS OF CHEMICAL ENGINEERING TECHNOLOGY

To the University of Johannesburg, Department of Chemical Engineering is, apart from the recognised assistance of my supervisors, my original work and that I have not previously in its entirety or in part submitted it at any University for a degree.

Signature: ……………….

Date: 26th February, 2015

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ABSTRACT

The design process was carried out in two stages: feedstock analysis and system design. Under feedstock analysis, the study investigated the amount of the organic fraction of municipal solid waste **(**OFMSW) generated at the study area which was situated at the University of Johannesburg's Doornfontein Campus (UJ DFC) in downtown Johannesburg South Africa. Furthermore, the feedstock analyses involved characterisation studies on the target waste under which several laboratory tests were undertaken. The system design involved sizing of the suitable biogas digester to be used in the system applying mathematical models and feedstock parameters obtained from the feedstock analyses. Via the application of the Simple Multi-Attribute Rating (SMART) technique of multiple-criteria decision analysis (MCDA) as a decision support tool, the most preferred option of biogas plant model was selected from a list of potential alternatives available on the market. And, in addition, a suitable site around the study area was selected by applying the analytical hierarchy process (AHP) technique of MCDA. Other system components and accessories such as the piping, scrubbers and valves were sized, selected, integrated into the system and finally layout drawings were produced using Inventor computer aided drafting (CAD) Software. Furthermore, feasibility assessments were conducted on the proposed system such as energy usage assessments and economic analyses using the net present value (NPV), internal rate of return (IRR) and benefit-cost ratio (BCR) techniques.

The UJ DFC was found to generate 378 kg of municipal solid waste per day of which 231.22 kg was the organic fraction composed of food waste and garden waste. The waste had a density of 775 kg/m^3 with a total solids (TS) content of 27.14%, volatile solids (VS) content of 94.9% and C/N ratio was 1:25 requiring a biogas digester of 30 m^3 capacity to be treated. Biomethane potential tests showed that the feedstock had a biogas generation potential of 386.46 ml/g VS at 62% methane content. Fourteen (14) digester models were evaluated and the most preferred choice for the project was the Puxin digester. On the other hand, preliminary site selection yielded three (3) potential alternatives of which the site close to the Aurum ladies' residence turned out to be the most preferred choice at which the produced gas would be used for heating purposes to substitute liquefied petroleum gas (LPG). An energy evaluation of the feedstock showed that the system had a potential to produce a surplus of 51.3 MWh of energy annually and economic analyses over a 20 year economic period showed that the system was economically viable with a breakeven period of 4 years, BCR of 1.86, IRR of 31% and a positive NPV of R479, 111. It is recommended that the economic viability of the project can further be improved through the introduction of more revenue streams to maximise the project benefits such as the inclusion of carbon credits as well as government subsidies.

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ACRONYMS

AD	Anaerobic Digestion
AHP	the Analytic Hierarchy Process
ANP	the Analytic Network Process
BCR	Benefit Cost Ratio
CBR	Case-based Reasoning
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
DFC	Doornfontein Campus
DS	Decision Support
FAO	Food and Agricultural Organisation
GHG	Greenhouse Gas
FIRR	Financial Internal Rate of Return
HRT	Hydraulic retention time
H_2S	Hydrogen sulphide
MCDA	Multiple-criteria Decision Analysis
MCDM	Multiple-criteria Decision Making
MDG	Millennium Development Goals
MSW	Municipal Solid Waste
NPV	Net Present Value
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Optimum Organic Loading Rates
SABIA	Southern African Biogas Industry Association
SANEDI	South African National Energy Development Institute

SMART	Simple Multi-Attribute Rating Technique
TS	Total Solids
UJ	University of Johannesburg
UN	United Nations
VS	Volatile Solids
WFR	Weighted Factor Rating

CHAPTER 1: INTRODUCTION

1.1 General Background

The global energy demand has recorded exponential growth over time with a predicted 85% increase between the years 2010 and 2040. Approximately 85% of the world's energy supply is obtained from non-renewable fossil fuels sources such as coal, oil and natural gas. These fuels yield high quantities of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). The continuous use of fossil fuels is leading to the long-term potential risk of energy insecurity and simultaneously degrading the environment with the high CO_2 emissions [1]. Figure 1 shows the graphical representation of the world's primary energy consumption by source between 1987 and 2012. It shows a general growth in energy consumption and fossil fuels continue to lead currently at over 84% with renewables as the least used source [2].

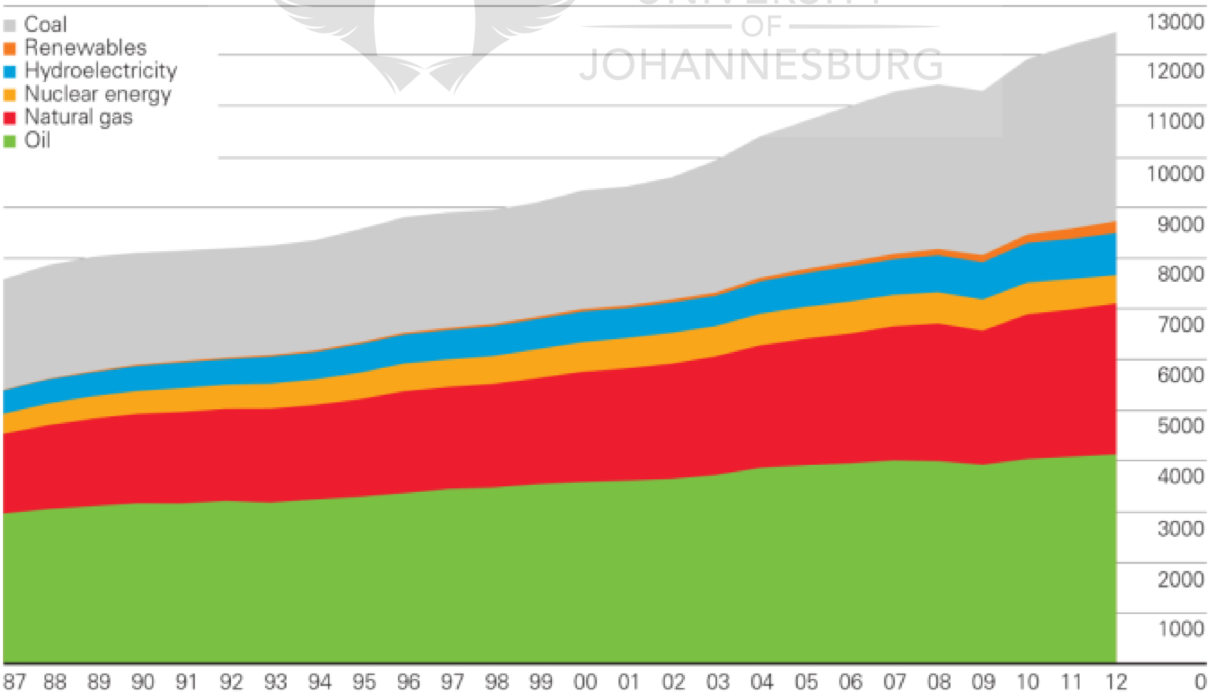

Figure 1: World primary energy consumption by source in million tonnes oil equivalent (mtoe) [2].

According to the 2013 report published by the United Nations on the Millennium Development Goals (MDGs), environmental sustainability was under severe threat as the carbon dioxide emissions continued to accelerate [3]. Currently, the rate of carbon dioxide emissions is 46% higher than the levels recorded in 1990 while the rate of deforestation continued at an alarming rate. [3].

To successfully combat the current problems of energy insecurity and environmental degradation, the world needs to diversify its energy sources by looking further than the traditional non-renewable sources like fossil fuels. This can be accomplished by investing in new green technologies that promote the use of renewable energy such as the production and use of biofuels from biomass, solar power from the sun, wind energy, hydro power and geothermal power among others [4]. The synthesis of biomass to produce energy is a growing trend worldwide as the quest for clean energy alternatives instead of the traditional fossil fuels intensifies. In this regard, there have been several technologies developed such as the synthesis of bioethanol from sugar rich energy crops such as corn, the making of biodiesel from vegetable oils and animal fat, pyrolysis and gasification of biomass as well as the anaerobic digestion of biomass among others [5].

A report by the Food and Agricultural Organisation (FAO) of the United Nations (2008) indicated that increased use of food crops for bioenergy production in a bid to increase its supply will lead to increased food prices. Although this may significantly promote growth of agricultural economies in the short run, in long term it will lead to food insecurity in developing nations [6]. Therefore, to prevent the risk of increased global food insecurity, alternative types of biomass for bioenergy production should be introduced other than food crops [7]. In this context, other energy crops such as Jatropha have been proposed for bioenergy production [8]. But just like food crops, all planted biomass requires resources such as land and water so as to meet the requirements of a reliable and sustainable substrate supply and yet both land and water are also very vital resources for the global energy balance. This, therefore, disqualifies planted biomass as the most preferred source of biomass for bioenergy production [9]. Other than energy crops, bioenergy can still be recovered from biodegradable waste via various energy recovery techniques such as anaerobic digestion (AD), Incineration, pyrolysis and gasification among others [10]. It is in this view, the concept of biowaste for energy production becomes a potential solution towards the production of an alternative environmentally friendly and sustainable energy [9, 11].

Globally, urbanisation is on the increase leading to increased municipal solid waste (MSW) generation and reduction in available space within urban centres. The waste generated is commonly sorted for recycling and the non-recyclables, which are usually the larger percentage are taken to landfills. The issue now is the continuously reducing space for landfilling as well as the continuous emissions of landfill gas containing mostly methane which is a potential greenhouse gas (GHG) [12]. The possibility of bioenergy production from OFMSW represents a scenario where an alternative source of clean energy is obtained, GHG emissions are reduced while simultaneously minimising the nuisance of solid waste [5].

In response to the above challenges, several techniques have been developed for the conversion of waste to energy including incineration of the waste by combusting the waste at high temperatures to produce heat, pyrolysis/gasification of the waste to produce combustible gasses and the anaerobic digestion of the biowaste using microorganisms to produce biogas a valuable energy source [13]. Among the current waste-to-energy conversion techniques, anaerobic digestion of biowaste gives the highest energy net yield and more consideration to environmental conservation. Incineration, gasification and pyrolysis tend to yield more energy within the shortest times as compared to anaerobic digestion, but the former also require higher energy inputs since the organic matter is reacted at very high temperatures [14]. In addition, anaerobic digestion of organic waste is the one technique that recovers energy, conserves the original water content of the feedstock and produces a nutrient rich organic agricultural fertilizer in the form of a digestate unlike the other methods which burn off the water and produce toxic carbon and heavy metal rich by-products [15-17]. Mata [18] showed that anaerobic digestion is the most successful waste-to-energy technique for the treatment of wet wastes of moisture contents higher than 60% whereas Kunte et al [19] showed that AD is the single most effective approach for pathogen removal from organic wastes especially in multi-stage systems.

1.2 Project Background

Funded by the South African National Energy Development Institute (SANEDI), the University of Johannesburg's Doornfontein Campus (UJ DFC) in South Africa undertook a research project to study the potential of biogas produced from the organic fraction of municipal solid waste (OFMSW) as a vehicular fuel. Part of the project involved the implementation of biogas digesters at demonstration and pilot scales utilising the organic fraction of municipal solid waste as the targeted feedstock. The integration of an anaerobic digester into the University campus' solid waste management (SWM) system would reduce the costs of SWM as well as safe guard the environment from greenhouse gas emissions resulting from landfilling. The digester would also produce biogas which would be used as a renewable energy source increasing the University campus' overall energy supply.

Despite the efficiency of the existing solid waste management system (SWM) at the UJ DFC, all the organic municipal solid waste collected (which is the largest percentage) is transferred to landfills. Therefore, the University incurs costs to dispose of the largest portion of its waste. In addition, the landfilled waste later on produces methane gas (a potential greenhouse gas) on compositing at the landfill leading to destructive effects to the atmosphere. This calls for practical environmentally sustainable solutions such as anaerobic digestion (AD) to treat the generated biowaste while simultaneously utilising the generated biogas from the digestion as usable clean energy.

1.3 Objectives

1.3.1 General Objective:

To design a pilot scale anaerobic biogas digester system utilising the organic municipal solid waste generated at the University of Johannesburg's Doornfontein Campus (UJ DFC) and produce biogas to be utilised locally.

1.3.2 Specific Objectives:

- To categorise the various waste streams and undertake a detailed waste quantification exercise at UJ's Doornfontein campus,
- Undertake detailed characterisation of the target feedstock to establish key input parameters for biogas production and anaerobic biodigester design,
- Predict biogas production from the organic waste using the obtained data,
- Use the obtained results to design a pilot scale biogas anaerobic digestion system at the University's Doornfontein campus,
- Undertake an assessment of the system energy usage and thereafter an economic analysis to check the system's feasibility.

1.4 Scope of the Study

Geographically, the study was limited to the confines of the University of Johannesburg's Doornfontein campus (UJ DFC) in downtown Johannesburg, Gauteng province, South Africa. Scientifically, the study focussed on the utilisation of the OFMSW generated at the school campus as a feedstock for biogas production to be used within the same area. This was achieved via the detailed analysis of the OFMSW samples to ascertain their basic properties as feedstock for biogas production and finally a design of an appropriate biodigester to treat the envisaged feedstock quantities and quality was developed. Figure 2 shows a satellite image the UJ DFC.

Figure 2: View of UJ DFC from a google maps satellite image in downtown Johannesburg, South Africa

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter represents a review of existing literature and previous studies on biogas technology with particular emphasis on its production from OFMSW as primary feedstock.

2.1 The Concept of Anaerobic Digestion and Biogas Production

2.1.1 General Overview

Biogas refers to the energy-rich gas produced from the anaerobic digestion (AD) of biomass using microorganisms. It has an approximate composition of 50-70% methane (a combustible gas), 30-50% carbon dioxide and other trace gases such as hydrogen sulphide (H_2S) depending on the target biomass feedstock [20]. The history of anaerobic digestion of biomass for energy production can be traced back to the 10th Century B.C with the earliest available record being around the 19th century. The first anaerobic digester was set up in India in the town of Bombay around the year 1859. On the other hand, in England, the first remarkable application of biogas as a fuel was also recorded in the same year 1859 [20]. Over the years, farm based manure has been the most extensively used feedstock for biogas production. However other sources have gradually been adopted as alternatives [5]. During AD, biomass (organic matter) is broken down by microorganisms in the absence of air. Therefore, the process can artificially be set up within airtight vessels also known as anaerobic biodigesters or it can occur naturally at the bottom of ponds or marshes where there is successful air-deprivation [21].

Biogas is currently used in many developing countries as an alternative and renewable source of energy for wide spread range of applications. In contemporary times, biogas has been used most extensively in India and China. Currently in Germany, biogas technology is in advanced stages and being used to produce green electricity in the Mega Watt range. Economic production of biogas can be economically achieved for both large and small scale applications. Hence it can be designed to fit into rural, urban as well as regional and nationwide energy needs [5]. The quality of raw biogas can be further improved via various upgrading techniques to remove the non-combustible components and as a result increasing the methane content to approximate natural gas quality (75-98% methane). The biomethane produced from the enrichment and subsequent compression processes can be used as vehicular fuel among other applications. Biogas has much lower CO_2 emission rates than natural gas or any other fossil fuel, and consequently has less impact on climate change. It is however worthy noting that biogas produces higher NOx emissions than natural gas as shown in Table 1 [22].

Table 1: Comparison of Gaseous Emissions from Heavy Vehicles

g/kg	**CO**	**HC**	**NO_x**	**CO_2**	**Particulates**
Diesel	0.20	0.40	9.73	1053	0.100
Natural Gas	0.40	0.60	1.10	524	0.022
Biogas	0.08	0.35	5.44	223	0.015

2.1.2 Microbiology of Biogas Formation from Organic Matter

The microbial activity leading to biogas production from organic matter is carried out by a large complex set of bacteria that work independently. The methane-producing bacteria also known as methanogens are the most notable group. The process is broken down into three (3) stages, that is: hydrolysis, acidification and methane formation as discussed in the sections below [23];

2.1.2.1 Hydrolysis

At this stage the microorganisms externally enzymolyse organic matter using their extracellular enzymes such as cellulase, amylase, protease and lipase. The bacteria at this stage decompose the long and complex molecular chains of the proteins, carbohydrates and lipids into shorter and simpler intermediate products like monosaccharides, peptides and amino acids [10].

2.1.2.2 Acidification

In the second step, acid-producing bacteria are involved. These are responsible for the conversion of the simple intermediates from the hydrolysis process into molecules of carbon dioxide (CO_2), acetic acid (CH_3COOH) and hydrogen (H_2). The bacteria at this stage can survive under both anaerobic and aerobic conditions as well as acid conditions. These bacteria utilise the dissolved oxygen or bounded-oxygen in the solution and carbon to produce acetic acid. By doing this, they create an anaerobic environment that is conducive for methanogenesis [23].

2.1.2.3 Methane Formation

This stage is controlled by the methane-producing bacteria also known as methanogens. These bacteria are responsible for the breakdown of the carbon dioxide, acetic acid and hydrogen that are produced during the acidification stage to produce methane and carbon dioxide. Methanogens operate in exclusively anaerobic conditions and are therefore sensitive to sudden environmental changes. In comparison to the acidogenic and acetogenic bacteria, methanogens have a rather heterogeneous morphology and several peculiar biochemical and biological properties that set them aside from all other genera of bacteria. Chemical reactions during methanogenesis can be summarised as in equations 1 and 2 [10];

$$CO_{2(g)} + 4H_{2(g)} \longrightarrow CH_{4(g)} + 2H_2O_{(l)} \qquad (1)$$

$$CH_3COOH_{(aq)} \longrightarrow CH_{4(g)} + CO_{2(g)} \qquad (2)$$

During biodigestion, the bacteria types involved work symbiotically. The activities and products of one set of bacteria support the other and vice versa. Therefore no particular set of bacteria acts in isolation, they all work in synchronisation. When the acid producing bacteria use up the oxygen to create light compounds, it creates an anaerobic environment for the methanogens as well as simpler and less complex compounds. On the other hand, the methanogens utilise the intermediate products from acidification thereby eliminating the possibility of creation of toxic conditions for the acid-producing microorganisms [24]. The processes can be summarised as in Figure 3 [25];

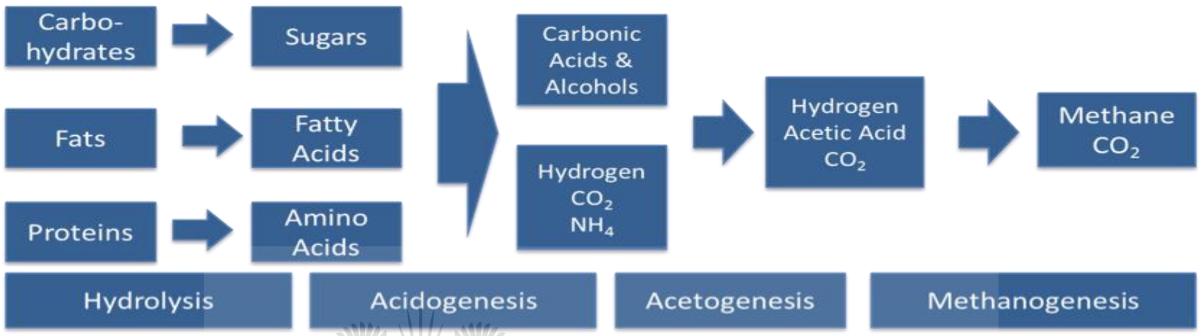

Figure 3: Anaerobic Digestion process

2.1.3 Conditions for Anaerobic Digestion

The various factors affecting methane production from anaerobic digestion are given in detail below;

2.1.3.1 pH;

Methanogens thrive best under neutral and slightly alkaline environments. They are killed by acidic conditions. During hydrolysis and acidification, large quantities of organic acids accumulate in the system; this in turn leads to the pH inside the digester dropping to low values in the acidic range below 5 which inhibits the digestion process by killing off the methanogens. However, as the AD process progresses; ammonium concentration builds up as a result of nitrogen synthesis which in turn raises the pH to over 8. Upon stabilisation of the AD process, the pH in the system will be in the range of 7 and 8.5 [10, 26]. Liu et al [27] showed that the optimum pH for anaerobic process is 6.5-7.5 and that the biomethane production increased by an estimated 35% in the optimal range and Jain and Mattiasson [28] also showed that for pH values above 5, the efficiency of biomethane production increased to more than 75%.

2.1.3.2 Temperature

Optimum performance of an AD system is influenced greatly by the operating temperatures of the digester. The various temperature ranges within which optimal AD performance occurs are categorised as; Psychrophilic (< 30°C), Mesophilic (30 – 40°C) and Thermophilic (50 – 60ºC) [29]. Previous studies have however showed that anaerobic bacteria exhibit the highest activity within the mesophilic and thermophilic ranges [5]. Extreme cases of either very high or very low temperatures kill of the anaerobes hence inhibiting the whole AD process. The optimum temperature is 35°C [21, 26].

2.1.3.3 Feedstock Composition and Nutrients

Several varieties of biomass feedstocks can be utilised by AD systems such as agricultural crops, animal manure, human waste, municipal sewerage and biowaste among others. The nature of the feedstock used determines the quality and quantity of the biogas yield [5]. In addition to the biogas yield, biomass produces carbon and essential nutrients that facilitate the sustainable growth of the microbes. However, other than the biomass, the bacteria require extra mineral nutrients for optimal performance in addition to the hydrogen, oxygen and carbon. Such nutrients include; potassium, Zinc, Calcium, Cadmium, nitrogen and phosphorus among others. Agricultural based residues and biowastes usually contain adequate amounts of these elements [5]. Kumar et al [30] showed that the biogas yield as a result of anaerobic co-digestion of cattle manure and potato waste increased with the addition of heavy metals and that the greatest increases were recorded from Cadmium addition followed by Nickel II and lastly Zinc.

2.1.3.4 Loading Rate

The loading rate can be defined as the unit quantity of feedstock supplied per unit volume of biodigester per day. Biogas yield is also highly dependent on the loading rate. Studies have shown that methane yield increases with a reduction in the loading rate. At high loading rates, the bacteria get overwhelmed since there tends to be excess substrate than what the bacteria can breakdown. In the event that the loading rate is higher than required, the biogas yield will initially spike up and then suddenly fall shortly due to process inhibition [21].

2.1.3.5 Carbon/Nitrogen (C/N) Ratio

Anaerobic digestion ideally occurs at C/N ratio ranges between 20:1 and 30:1. Methanogenic bacteria use nitrogen to meet their protein requirements. Therefore in cases of high C/N ratios higher than the optimum ranges, the nitrogen will be depleted rapidly by the bacteria and hence will not react on the excess carbon in the feedstock thereby reducing the biogas yield. For cases of lower ratios than the desired range, the excess Nitrogen will result into Ammonia (a strong base) formation hence raising the working pH over the desired 8.5 inhibiting the microbes and ultimately dropping gas production rates [5].

2.1.3.6 Particle Size

The substrate for anaerobic digestion should be composed of digestible particle sizes. Smaller particles increase surface area for the microbial action of the methanogens thereby increasing the rate of biogas production as well as biodegradability of the feedstock. And the reverse is true for large particles which can clog the digester [31]. A study by Sharma et al [32] on the AD of a substrate using five varying particle sizes of 0.088mm, 0.40mm, 1.0mm, 6.0mm and 30.0mm, the highest biogas production rate was attained from the substrate at 0.088 and 0.40 mm particle sizes.

2.1.3.7 Agitation

The substrate has to be continuously stirred to ensure the even distribution of the anaerobes as well as intimate contact between the anaerobes and the substrate. This eventually improves the AD process since the activity is evenly distributed through the reactor. This can be achieved via several methods such as adopting continuous feeding of the digester rather than batch and mechanically by use of agitators installed within the digester or manually [26].

2.1.3.8 Moisture Content

The microorganisms' excretive and other essential metabolic processes require water to take place hence the feedstock should have optimum moisture content for performance of the bacteria. The optimum value of moisture content should be about 85% of the total volume of feedstock. Excess water in the feedstock leads to a fall in the biogas yield per unit volume of substrate and on the other hand, inadequate water leads to an accumulation of acetic acids that inhibit the AD process and hence overall yield. Furthermore, inadequate water will lead to scum formation on the surface of the substrate which may prevent effective mixing of the digester contents [5].

2.2 OFMSW as a substrate for biogas production

The amount and nature of feedstock to be used in the AD system for biogas production is the single most important factor to be considered in the system design. The volumetric yield of the gas per unit weight of the substrate added varies from one type of substrate to another depending on the composition as well as nature of the substrate. In addition, the percentage of methane obtained from the resultant biogas also varies independently according to type of biomass material. Therefore, to run an efficient biogas digester, a keen interest should be drawn on the availability and quality of biomass [10]. The yield of biogas in litres per kg of various materials is summarized in Table 2 alongside the percentage of methane production per raw material [33].

Table 2: Biogas Production Potential from different substrates

Raw Material	Biogas Production Litres/kg	Methane Content In Biogas (%)
Cattle Dung	40	60
Green leaves	100	65
Food Waste	160	62
Bamboo Dust	53	71.5
Fruit Waste	91	49.2
Bagasse	330	56.9
Dry Leaves	118	59.2
Non-edible oil seed cakes	242	67.5

2.2.1 Definition of Municipal Solid Waste (MSW) in South Africa

MSW also known as general waste, according to the National Environmental Management (NEM) Waste Act, 2008 (Act No. 59 of 2008) of South Africa is that waste that is not an immediate threat to human health or the environment. It includes; domestic waste, building and demolition waste, business waste; and inert waste. "There are five broad categories of MSW [34]. Namely:

- Biodegradable waste: food and kitchen waste, green waste, paper (can also be recycled)
- Recyclable material: paper, glass, bottles, cans, metals, certain plastics, etc.
- Inert waste: construction and demolition waste, dirt, rocks, debris.
- Composite wastes: waste clothing, Tetra Packs (polystyrene), waste plastics such as toys.
- Domestic hazardous waste & toxic waste: medication, paints, chemicals, light bulbs, fluorescent tubes, spray cans, fertilizer and pesticide containers, batteries, shoe polish."

Therefore OFMSW is composed up of kitchen waste and garden waste [34].

2.2.2 Waste Stream Characteristics of South Africa

According to the National Waste Information Baseline Report of 2012, as of November 2012, there had been a few nationwide waste characterisation studies undertaken in South Africa [35]. However, from the data collected, estimates of countrywide solid waste characteristics as of 2011 were obtained as shown in Figure 4 and Figure 5 [35]. The report showed that South Africa generated 59 Megatons of general waste in 2011 of which only 13% was the biodegradable fraction as shown in Figure 5.

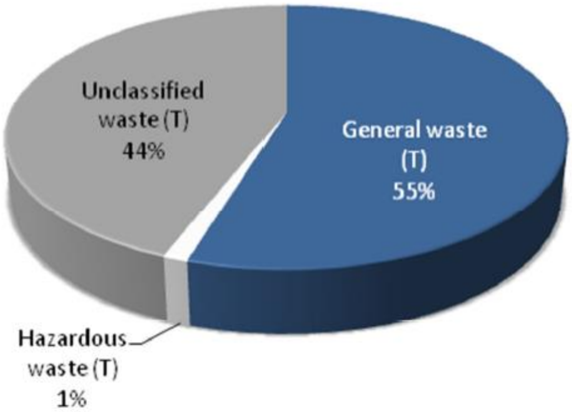

Figure 4: Waste composition as percentages of total waste generated in South Africa, 2011

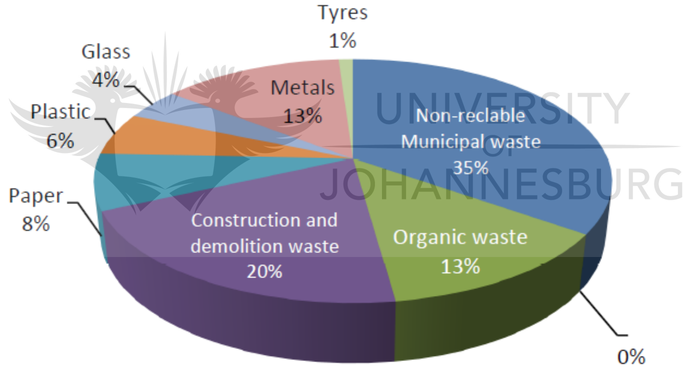

Figure 5: Waste composition as percentages of General Waste in South Africa, 2011

2.2.3 Benefits of OFMSW as a Feedstock in the Production of Biogas

2.2.3.1 Availability

Compared to energy crops that require extra costs to be grown and availed, OFMSW is readily available in abundance and is an inexhaustible substrate which requires minimal input to be ready as a raw material for biogas production. In most cases it will be availed at no extra cost since the anaerobic digestion can be incorporated into the existing waste management systems in which OFMSW is normally discarded to landfills as a useless component [9].

2.2.3.2 Tool for Environmental Conservation

The use of OFMSW for biogas production as discussed in the previous sections is a window of opportunity that helps to solve the current growing problems of solid waste management (SWM) in urban settings that are relying majorly on landfilling of the OFMSW that leads to methane gas emissions to the atmosphere. In addition, the anaerobic digestion process produces biogas a renewable versatile energy source that can substitute the traditional fossil fuels for heating, cooking as well as electricity generation. Fossil fuels are rich in carbon emissions and any clean energy alternative is of indubitable value to environmental conservation [36, 37].

2.2.3.3 High Total and Volatile Solids' Content

Total solids' (TS) content is the quantity of all solid matter in a given substrate. TS content of a substrate is obtained by weighing the residue or dry material left after drying it for 48 hours at 105°C. The mass obtained is the raw estimation of both the organic and inorganic content of the substrate [38, 39]. One other hand, volatile solids (VS) also referred to as the organic fraction of the total solids represent the digestible portion of the total solids normally expressed as a percentage of TS. VS is obtained by heating the TS at 550°C for 24 hours. What is lost is the VS content and what is left as residue from the process is the inorganic fraction of the TS [38]. OFSMW is a predominantly solid substrate with an average TS content of approximately 30% as well as relatively large particle sizes [36]. As opposed to farm manure, fresh OFMSW has not undergone any prior digestion processes therefore still has high energy content hence high concentration of digestibles also herein referred to as the volatile solids. This fact implies that OFMSW produces more biogas per unit weight than most wastes making it a more economical option for biogas production [12]. The high biogas yield per unit weight of substrate also means that for a target production rate of biogas, a smaller digester will be required than for the case of other substrates like farm manures and municipal sewerage hence a reduced overall cost of AD [40].

A study by Zhang et al [39] on the characterisation of food waste from the City of San Francisco in USA obtained daily average TS of 70% and VS of 83%, while the weekly averages were 74% and 87%, respectively. A study by Cho et al [37] on the anaerobic digestion of kitchen waste in Korean showed a high range of TS and VS with VS values ranging between 90-95% of TS and TS values averaging 30%.

2.2.3.4 High Biogas Yield

Values from literature indicate that depending on the composition of the OFMSW, the substrate can yield approximately anywhere between 300 to 500m^3 of biogas per tonne of volatile solids at 65% methane [12]. The average biogas production from OFMSW is 367m^3/tVS [36]. Table 3 shows the various biogas yields as quoted from various sources.

Table 3: Various experimental biogas production rates for OFMSW

Feedstock	Production rate (m^3/tVS)
Organic Solid Waste	310-490 [12]
Kitchen waste	367 [36]
Organic Solid Waste	300-400 [41]
Organic Solid Waste	310-490 [12]
Organic Solid Waste	390 [42]
Food Waste	355 [12]
Food Waste	472 [37]

2.2.3.5 Good Quality of Biogas

The quality of biogas is measured by the methane (the combustible gas) content of the biogas which ranges between 50-70% [33]. At an average of 65% composition of methane [41], the biogas produced from the biodigestion of OFMSW is high grade compared to most substrates such as cattle dung at 60% [33] as shown in Table 2.

2.2.3.6 Higher Organic Loading Rates (OLR)

OFMSW gives optimum anaerobic biodigester performance at organic loading rates between 5-10 kgVS/m^3 [39, 41]. Experimental work by the East Bay Municipal Utility District under the EPA in 2008 on municipal wastes showed that anaerobic digestion of OFMSW can occur at significantly higher OLR values ranging between 5 to 105 kgVS/m^3-day and average of 8.5 kgVS/m^3-day whereas typical municipal wastewater recorded a range of 1.6 to 3.2 kgVS/m^3-day [36].

2.2.4 Limitations of Using OFMSW as a Substrate for Anaerobic Digestion

2.2.4.1 Heterogeneity

Unlike most AD substrates, OFMSW is a very complex type whose composition is highly unpredictable [12]. OFMSW can contain a wide spectrum of components from basic food waste, garden waste (leaves and stalks), paper and residual inorganics also referred to as contaminants like metals, glass, dust, stones and plastics among others varying according to season and location [43].

As noted in the earlier sections, the efficiency of an anaerobic digestion process primarily depends on the composition of the substrate [10]. However, OFMSW is a very complex substrate whose composition is highly unpredictable [12]. To be able to obtain a quality feedstock for anaerobic digestion from OFMSW, a thorough sorting procedure has to be designed and set up which can be anything from source sorting to the integration of hydro-mechanical equipment like trommel screens, hydropulpers and hydrocyclons among others [44]. The sorting involved in OFMSW is a costly and time consuming input that escalates the costs of the overall process which would otherwise be avoided if less complex substrates like farm manure or sewerage sludge were used. The mechanical sorting equipment increase the initial capital costs, overall system power demand as well as the plant operation and maintenance cost [43].

Arsova [44] conducted studies on five AD plants of OFMSW three in Spain and two in Canada all using somewhat varied sorting criteria. The economic analyses of these revealed that the high capital and maintenance costs of the AD facilities coupled with the small returns recouped from the applications of biogas and its by-products, the gate fee for at the waste treatment facility would be in the range of $100-150 for a ton of waste. Considering the average landfill gate fees at the time in U.S. of USD 42 per ton, the AD facilities had to be subsidised for economic feasibility.

2.2.4.2 Large Particle Sizes

With particle sizes of up to 100mm, the pumpability and agitation of OFMSW are rather difficult processes compared to more fluid and finer substrates like farm manure. In addition, large particle sizes reduce the surface area for microbial activity making the system inefficient [12]. However, particle size reduction of OFMSW can be achieved by incorporating shredders and grinders prior to feeding the biodigester which increases the project costs. The direct costs aside, any additional equipment onto the AD system have power requirements too [38].

Curry et al [45] designed and implemented an AD system at Concordia University downtown Montreal, Quebec Canada. For system efficiency, the system had to incorporate a mechanical pre-treatment assembly comprising of a grinder, mixer and a biofilter. These combined had a power demand of up to 943.6kWh/year and would cost the project an extra USD 30,310 annually.

2.2.4.3 Acidity

OFMSW substrates are characterised by low pH levels below the optimum 7 due to high concentration of volatile fatty acids from oily and meaty food wastes [46]. This can however be counter balanced by pre-treatment of the substrate with a controlled amount of alkali solutions like Sodium hydroxide to raise the initial pH of the substrate above 7 [47].

A study carried out by Stenstrom et al [48] on anaerobic digestion of OFMSW revealed that the AD process was very sensitive and that the digesters would easily be overloaded and produced high quantities of volatile fatty acids (VFA). However, it was further illustrated that the failures in the AD process could be mitigated by pH control using alkaline solutions such as sodium carbonate and by reducing the loading rates temporarily. In extreme cases, the digestate from the system would be recycled to ensure recovery.

2.2.4.4 Complexity of Urban Settings

An efficient biogas generation system is usually one in which the substrate, the biodigester and user are all located in the same place to minimise costs. However, for most urban areas where OFMSW is generated, the space available is minimal and permanent utilities have already been set up making incorporation of biogas digesters quite difficult as opposed to rural settings [44]. On the case of Curry [45], the AD system was set up in the middle of downtown Montreal and therefore special attention had to be given to existing utilities such as gas lines and fire points. These introduced extra costs of set up with items such as relocation of old ventilation systems, gas safety and digestate management.

2.2.5 Economics of Anaerobic Digestion of OFMSW for Biogas Production

Biogas Technology has mostly been disseminated by non-profit organisations (such as SNV, FAO, GIZ) or government institutions, because over the years, economic analyses have revealed that the high initial investment costs as well as operation and maintenance costs limit its feasibility as an investment unless subsidies are provided to the investor. Biogas projects are usually characterised by long breakeven periods and yet the direct commercial benefits are usually small given the competition from existing energy sources like fossil fuels which also discourages investors. One of the ways to make biogas plants profitable is by complimenting revenues from gas production with sales on the digestate as a fertilizer as well as claiming carbon credits [49].

The other way that can improve the economic feasibility of AD technology is by increasing the scales of production. At larger scales, the costs of production essentially go down. Evaluations on AD plants of OFMSW in Europe indicated that a 100,000 ton per year plant would operate economically charging €30 for every ton of organic waste treated while on the other hand, a

20,000 tons per year plant would only achieve similar economic viability if the charge per ton of waste treated is doubled to €60 [43]. Due to the heterogeneous nature of OFMSW, AD systems utilising OFMSW as their primary substrate usually cost more than when other homogeneous substrates are used such as farm manures due to the extra costs usually involved in substrate pre-treatment so as to improve its properties for efficient AD system performance such as grinding for particle size reduction, sorting for contaminants removal and alkali pre-treatments for pH control among others [39, 43].

2.2.6 Substrate pre-treatment for anaerobic digestion

Substrate pre-treatment refers to all the processes that the feedstock undergoes prior to use in anaerobic digestion. These processes range from physical ones like sorting and particle size reduction to chemical processes like alkali treatment and metal addition among others [38]. Pre-treating feedstock for AD can result into increased biogas production rates as well as volatile solids reduction [50]. Usually, the performance of AD systems is expressed as the rate of biomethane production under pre-set conditions per unit weight of substrate. The various performance enhancers are as elaborated below [51];

2.2.6.1 Seeding

Seeding is a way of kick-starting a newly commissioned biogas plant by feeding it with previously digested material from another established set up. Alternatively, materials such as animal manure or municipal sewerage are often used to seed a newly commissioned biogas digester, so as to reduce the plant start-up time. The method aims to introduce inoculum into the system [26].

2.2.6.2 Particle Size

The particle sizes of the substrate directly affect digestion as it has direct indications on the available surface area for hydrolysing enzymes especially with plant fibre. Methane yield and fibre degradation have been found to improve with decreasing particle sizes within the feedstock from 100 mm to 2 mm [31].

2.2.6.3 Alkali Pre-treatment

A study by Taherdanak and Zilouei [47] found that addition of controlled doses of alkali solutions in AD substrates was found to enhance biogas yield and at the same time reducing cellulose production especially when using plant material as feedstock. Clarkson and Xiao [52] proved that the rate of degradation of paper waste in AD systems increases by addition of optimum amounts of Sodium hydroxide (NaOH) solution. However, alkali solutions often lead to saponification reactions in continuous plants. These reactions tend to yield generate compounds leading to tremendous drops in acetate and glucose degradation rate.

2.2.6.4 Addition of Metals

Kumar et al [30] studied the impact of adding Cadmium (Cd^{2+}), Nickel II (Ni^{2+}) and Zinc (Zn^{2+}) in the anaerobic co-digestion of a combination of cattle manure and potato waste. The results showed the biogas yield was enhanced greatly with the highest increases recorded with Cd^{2+} to Ni^{2+} and lastly Zn^{2+}.

2.2.6.5 Thermal/Thermochemical Pre-treatment

Pre-heating of substrate before anaerobic digestion has proved to improve methane production as well as volatile solids reduction. Studies have also showed that pre-heating of substrate that has been treated with chemical additives (thermo-chemical) even gives better results [53]. Ardic and Taner [54] showed that pre-treatment of chicken manure with pre-heated Sodium hydroxide at 100^{o}C enhanced both the bio-methane yield as well as the biodegradability of the feedstock.

2.2.6.6 Ultrasonic Pre-treatment

Commonly used in sewage sludge treatment, the feedstock is treated using ultrasonic sound waves. Generally the method has been found to improve biogas production from anaerobic digestion. This technique introduces ultrasonic cavitation into the system that in-turn builds up mechanical shear forces that ultimately aid the sludge dis-integration as well as the collapse of cavitation bubbles which improve the feedstock's physical properties. However, the option is relatively more expensive than mechanical techniques such as milling, grinding or agitation among others hence not a preferred pre-treatment option for OFMSW [50].

2.2.7 Measuring biomass availability

The availability of biomass (biodigester feedstock) can be determined using several approaches. All these methods used independently can yield varying results. The techniques used include direct measurements of the feedstock from source, use of existing data from literature and references from previous studies. However, physical measurement gives the more accurate results since they are obtained first hand [40]. A report by the United Nation Environmental Programme (UNEP), 2009 mentions the following options [55]:

- Measurement at the point of generation,
- by examination of records at the point of generation,
- through use of vehicle survey and by
- Examination of records at the disposal facility.

The report goes on to emphasise that measurement at point of generation is the one method that can give the most accurate and reliable results. However, it is also the most expensive and time consuming approach. This method involves visiting the points where waste is generated and determination by measurement or observing the amount of waste disposed during a given period of time using appropriate sampling procedures [55].

2.2.8 Estimation of Biogas Production

It is necessary to predict the amount of biogas and its methane content that can be obtained from a given substrate so that preliminary designs can be developed as well as determine economic feasibility. There are several methods for predicting the probable outcome of anaerobic digestion of given substrates, these include;

2.2.8.1 "Ultimate Analysis"

Using specialised equipment or referring to literature, the elemental composition (i.e. Carbon, Hydrogen Nitrogen Oxygen and Sulphur) of a given substrate can be ascertained. Buswell and Mueller in 1952 developed a theoretical model that can be used to predict the molar proportions of the various products of anaerobic digestion of a given substrate whose CHNOS elemental compositions are known. The equation is as below [56].

$$C_cH_hO_oN_nS_s+\left(c-\frac{h}{4}-\frac{o}{2}+\frac{3n}{4}+\frac{s}{2}\right)H_2O\rightarrow\left(\frac{c}{2}+\frac{h}{8}-\frac{o}{4}-\frac{3n}{8}-\frac{s}{4}\right)CH_4+\left(\frac{c}{2}-\frac{h}{8}+\frac{o}{4}+\frac{3n}{8}+\frac{s}{4}\right)CO_2+nNH_3+sH_2S \qquad (3)$$

However, it is important to note that the value of the biomethane yield obtained from the model is theoretical and that the equation does not consider the solubility of the gases and ignores any AD inhibition factors such temperature and pH. Furthermore, the equation assumes 100% biodegradability of the organic matter and maximum HRT; hence to get reasonable results, the obtained results have to be corrected by the degradability factor of the substrate (usually 40-65% for OFMSW)[12].

2.2.8.2 Computer Simulation

Since Buswell's development in 1952, there have been several developments of computer models to try to model biochemical anaerobic digestion. Remarkable breakthroughs have been made over the years depending on the current advancements in computer technology like the Activated Sludge Model #1 (ASM1) by the International Association on Water Pollution Research and Control (IAWPRC) in 1987 for characterisation of waste sludge which was followed by more refined versions to produce the ASM2 in 1995, ASM2d in 1999 and ASM3 in 2000 [57, 58].

In 2002, to incorporate the latest development in computer technology as well as the better comprehension of AD systems into the ASM family of models, the International Water Association (IWA) developed the Anaerobic Digestion Model #1 also known as the ADM1.

Owing to its improved accuracy in determination of methane yields, the ADM1 is the most commonly applied model in recent times for analysis of AD systems because of its improved accuracy. The model uses laboratory determined parameters of the substrate that are input using computer languages like C and environments like Matlab-Simulink [12, 59].

2.2.8.3 Laboratory Digestion Tests

Using reliable samples of the intended substrates, these can be digested on a laboratory scale set up using batch digestion apparatus. The gas production can then be monitored using gas chromatography equipment to give an accurate estimate of the biomethane production [39].

2.3 Biogas Digesters

Biogas digesters are specifically designed air-tight bioreactors for the anaerobic digestion of organic matter to produce biogas [60].

2.3.1 Planning for a Biogas Digester

Just like any other project, setting up a successful biogas plant requires adequate planning to prevent any likely failures. The steps involves in the planning process for a biogas plant can be summarized as below [21, 23].

- Firstly, the designer has to make a clear understanding in terms of the energy demand and intended use at the targeted point of application.
- Thereafter, make conservative estimates of the biogas-generating potential of the planned set up on the basis of the quantities and quality of the given feedstock.
- A comparison should be made between the energy demand values as well as the energy capacity of the plant to check feasibility. Ideally the capacity of the plant should be over and above the envisaged energy requirements for a feasible project.
- Finally, based on the outcome of the first three steps, the designer can then embark on the sizing of the plant (digester, gasholder, etc.).

2.3.2 Parts of a Biogas plant

A biogas unit is made up of four (4) major components. Namely; reception tank, digester, gas holder and an overflow tank [5]. Figure 6 shows the major components of a typical biogas unit [40].

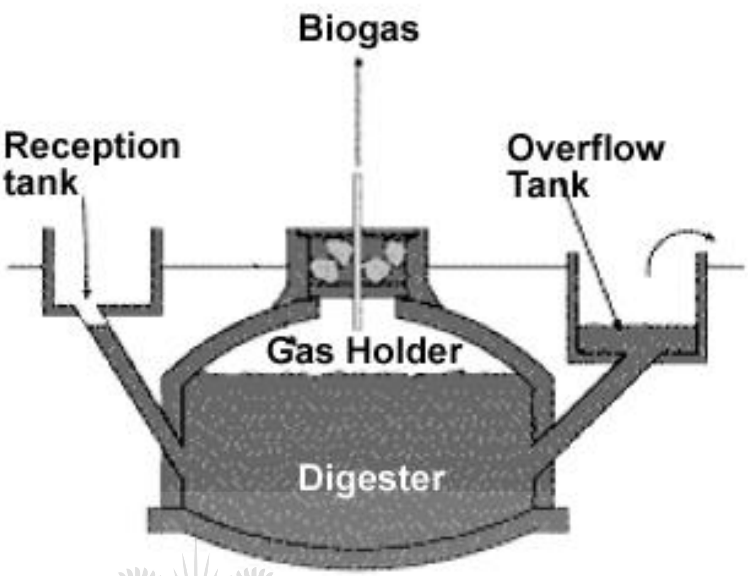

Figure 6: General Layout of a Chinese fixed-dome biogas unit

2.3.2.1 Reception Tank

This is the part of the biogas plant that receives the feedstock which is directed through an inlet pipe into the digester. The mode of feeding can be via gravity, feed screw or by hydraulic action. The size and shape of the reception tank is majorly dictated by the nature and volume of feedstock. At large scale plants, this is equipped with agitators and grinders to homogenise the feedstock. Some reception tanks incorporate pre-heating devices to minimise the negative effects of temperature shocks within the digester [60].

2.3.2.2 Digester

This is the chamber where anaerobic digestion takes place to produce methane and carbon dioxide. It is usually insulated to ensure optimal operating temperatures for the system. The choice of material used to construct the chamber entirely depends on the design of the digester and required capacity of the digester; it can be built from concrete, brickwork, steel or plastic.

In large scale AD systems, the chamber is very often equipped with electro-mechanical agitators to ensure intimate mixing of the substrate [40, 60].

2.3.2.3 Gas-holder

This is the facility where the produced gas is temporarily stored before it is discharged. Usually made of flexible material and protected from weather [40, 60].

2.3.2.4 Overflow Tank

After digestion, the digested slurry is collected in a store before it can be reused. Usually the slurry is used as a fertilizer in crop fields or redirected to sewer lines within the vicinity of the plant [60].

2.3.3 Conditions Affecting the Choice of a Biogas Plant

Developing a biogas plant design is essentially the final stage of the planning process. However, it is mandatory for the designer to familiarize themselves with basic design considerations in advance. Ultimately, a successful plant design should be able to respond to quite a number of factors, and these include [5, 40].

2.3.3.1 Climate

The design should respond to the prevailing climatic conditions of the location. Bearing in mind that biogas plants operate optimally at temperature ranges between 30°C to 40°C, in cooler regions, it is advisable for the designer to incorporate insulation and heating accessories to the design [21, 40].

2.3.3.2 Substrate Quality and Quantity

The type and amount of substrate to be used on the plant will dictate the sizing of the digester as well as the inlet and outlet designs [5].

2.3.3.3 Construction Materials availability

If the materials required for the plant set up can be sourced locally at affordable rates so as to maintain the plant set up costs within manageable ranges, then the design is preferred to that whose materials have to be imported [60].

2.3.3.4 Ground Conditions

Preliminary geotechnical investigations can guide the designer on the nature of the subsoil. In cases where the hard pan is a frequent occurrence, the design installation plan must be done in such a way that deep excavations are avoided because this would then increase the construction costs tremendously [5].

2.3.3.5 Skills and Labour

Biogas technology is sophisticated and hence requires high levels of specialised skilled labour. The labour factor cuts across from the planner to the constructor up to the user. However, gaps can be reduced through training of the involved parties at a cost [5].

2.3.3.6 Standardisation

Prior to commissioning of the design, the planner must carefully study the prevailing standards already on the market in terms of product quality and pricing especially for large scale projects [40].

2.3.4 Factors considered for choosing a biogas plant site

To plan a successful implementation plan for a biogas plant, special attention should be given to the choice of site where the plant is planned to be erected. The choice of area should be able to respond to quite a number of factors, and these include;

2.3.4.1 Area

The proposed site should have adequate space to accommodate the envisaged size of digester along with any its accessories such as connections, CHP generators and substrate agitation attachments among others as a full system [61].

2.3.4.2 Proximity to Substrate and Water Sources

The intended substrate or feedstock intended for use in the digester should be generated as close as possible to the plant site to minimise on the cost of feedstock transportation. Ideally, the biogas plant should be set up in the same vicinity as the feedstock source such as landfill in case of municipal solid waste or a cattle farm for manure [62].

2.3.4.3 Proximity to Point of Service

Combustible gases burn better at high pressures. Biogas just like any other fluid moving over a considerable distance tends to have pressure drops. The longer the distance, the higher the pressure drop. To ensure optimum gas pressure over a long distance, hydraulic pumps have to be installed along the delivery pipe to step up the pressure. This in turn increases the overall cost of the project. Hence the most preferred choice of site should be the closest to the point of application so as to reduce such unnecessary additional costs as pumping [62].

2.3.4.4 Existing Utility Lines

Just like any other plant, the proposed site for the new establishment should be free of existing underground service lines such as water lines, telecom lines, underground sewers etc. Presence of these would increase the project cost in relocation especially if the construction involves deep excavations [63].

2.3.4.5 Land Use Pattern

The current land use pattern could dictate the suitability of a particular site for establishment of a biogas plant. For example a proposed site located in an industrial area would be a better option than a gazetted residential area [61].

2.3.4.6 Proximity to Digestate Disposal Site

The digestate from the anaerobic biomass is a potent source of organic agricultural fertilizer. This should therefore be discarded or applied for use within acceptable distances to reduce transportation costs. The ideal and most economical sites should be located near farm land where the fertilizer can be applied or better if it’s an area with ready market for the fertilizer [64, 65].

2.3.4.7 Property Rights

A proposed site for a biogas plant should have a clear ownership history void of ownership conflicts. Therefore prior to project implementation, all legal checks and ownership paperwork should be made to ensure a streamlined process of project implementation [61].

2.3.4.8 Accessibility

The proposed site should be accessible to allow for ease access for delivery of feedstock and evacuation of the digestate [61].

2.3.5 Biodigester Sizing

To size a biogas plant, a number of factors have to be put into consideration especially as regards the feedstock type as mentioned earlier. If the biochemical properties of the substrate such as VS and TS among others have been obtained, the major ruling parameters for plant sizing are the desired hydraulic retention time (HRT) as well as the optimum substrate organic loading rate (OLR) [45]. These factors and how they are used to size the biodigester have been discussed below;

2.3.5.1 Hydraulic Retention Time (HRT)

HRT is the time usually expressed in days that the substrate spends in a reactor under pre-set and controlled conditions. This period should be long enough to reduce much of the pathogens and to allow the maximum amount of gas to be extracted from the substrate. HRT is directly proportional to the digester volume as in equation 4 below [60];

$$HRT=V/Q \qquad (4);$$

Where;

V is the Digester Volume (m^3) and Q is the rate of substrate inflow (m^3/day)

2.3.5.2 Organic Loading Rate (OLR)

The OLR represents the quantity of organic material that is added to the biodigester within a given amount of time usually expressed volume per day. The expression for OLR is as shown in equation 5 [66];

$$OLR= (Q \times S)/V \qquad (5);$$

Where:

Q: Flow rate of input (m^3/day)

S: Concentration of VS in the input (kg/m^3)

V: Reactor Volume (m^3)

From the above equations, the size of the digester can be computed via the modified version of the OLR expression as:

$V (m^3) = [Q (m^3/day) x S (kg/m^3)]/OLR (kg/m^3/day)$

Usually the OLR of a given system is pre-determined basing on several factors among which are the pumpability of the substrate and its composition among others. Therefore, OLR governs the design and dictates the values for the HRT [12].

2.3.6 Operation and Maintenance of biogas digesters

A carefully designed AD system should be easily run and maintained without difficulty. However, this requires constant attention from the owners of the plant. Poor maintenance of the plant results into operational problems which can have effects such as reduction on the amount of biogas available for consumption. The following are examples of the activities that can be carried out in the running of an AD system to ensure its proper functionality [40, 60].

- The gas holder must be cleaned regularly cleaned so as to avoid the accumulation of solids that eventually reduce the gas storage capacity by taking up volume.
- Feeding of the plant must be done regularly at a predetermined rate so as to achieve regular gas production. However the operator should ensure that the substrate is of the right particle sizes and that it is free of impurities like non-biodegradables such as stones and plastics to prevent inlet and outlet pipe blockages as well as scum formation.
- The water used should not contain chlorine as chlorine kills bacteria, and this would render the digester useless, therefore rainwater harvesting is advised for households using biogas.
- The overflow tank should be kept clean by removing any overflowing slurry or else the outlet could get blocked and lead to pressure imbalances in the digester resulting into a back flow of the biogas through the inlet pipe.

- The careful selection of suitable feedstock coupled with sufficient agitation of the substrate often prevents the occurrence of scum in the digester. If scum occurs, the lid has to be opened and the scum removed manually.
- The inlet pipe should also be cleaned to remove any grass or plant material that would otherwise bring about difficulty in feeding the plant as there would be a blockage at the pipe.

2.4 AD Technology and Site Selection

2.4.1 Technology Selection Methods

Several methods have been developed to give unbiased results when it comes to decision making on a particular choice of technology. In principle, all methods are based on the steps as summarised below;

- Identification of the problem,
- Identification of stakeholders,
- Seeking the unbiased opinions of the stakeholders in the form of solutions to the identified problem. The identified solutions are treated as alternatives and the key performance indicators of the chosen options become the selection criteria,
- Modelling the obtained solutions so as to obtain impartial results through detailed analyses. At the modelling stage is when the decision maker decides on which particular selection method to employ basing on the nature of the problem at hand.

In modern times, technology designs are probabilistic in nature and the evaluation criterion is multi-dimensional therefore it calls for complex tools that can capture all the dimensions of a decision problem. Some of the existing technology selection methods are as explained below;

2.4.1.1 Multi-criteria Decision Analysis (MCDA)

MCDA is an approach employed by decision makers to make recommendations from a set of finite seemingly similar options basing on how well they score against a pre-defined set of criteria [67]. MCDA techniques aim to achieve a decision goal from a set of alternatives using pre-set selection factors herein referred to as the criteria. The selection criteria are assigned weights by the decision maker basing on their level of importance. Then using appropriate techniques the alternatives are awarded scores depending on how well they perform with regard to particular criteria. Finally ranks of alternatives are computed as an aggregate sum of products of the alternatives with corresponding criteria. From the ranking, a decision is then made [68].

There are several variations in MCDA techniques used currently employing mathematics and psychology. These include;

I. The Analytic Hierarchy Process (AHP)

AHP aims at organising and analysing complex decisions basing on their relative importance independent of each other. What sets AHP aside from the other techniques is the idea of including pair-wise comparisons of the individual alternatives against each other as well as the criteria to emphasise relative importance and independence[69, 70]. Saaty [69] developed a scale of 1-9 to score alternatives basing on their relative importance as shown in Table 4.

Table 4: Saaty's 1-9 Scale

Intensity	Definition	Explanation
1	Equal Importance	Two elements equally contribute to the intended objective
3	Moderate importance	Basing on judgement and experience one element is favoured over the other
5	Strong Importance	Basing on judgement and experience one element is strongly favoured over the other
7	Very Strong Importance	One element is very strongly favoured over the other and its dominance can be demonstrated in practice
9	Extreme Importance	The evidence favouring one element over another is of the highest order of affirmation

However, the major drawback of the AHP is the alteration of ranks also referred to as “rank reversal” in cases where new alternatives are introduced into an already analysed problem [69, 70].

II. Analytic Network Process (ANP)

ANP is a more generalised form of AHP. It’s different from AHP in that it incorporates interdependence of alternatives as well as criteria across the board. This makes it more applicable for use in real-life situations where selection criteria actually depend on each other for example the idea of acquiring a car can be governed by its cost, safety and comfort among other factors. AHP will look at each of these three factors independently and yet indeed the cost of the car might only be high because of improved safety features making the two criteria interdependent. AHP organises goals, alternatives and criteria as hierarchies whereas ANP represents them as networks. However, both approaches use the pair-wise comparisons technique for scoring and ranking of alternatives and criteria [69, 71].

III. Simple Multi-Attribute Rating Technique (SMART)

By applying the SMART technique, alternatives are ranked basing on ratings that are assigned directly from their natural scales. Take for example if a choice of an automobile has to be made, the prices of the different automobiles will be given in a common currency which will be evidently easy for comparison since it is directly numeric [72]. In situations where the units of measurement for the weights of the criteria for given alternatives are not of a common scale, the decision maker has to create a unifying function referred to as a “value function”. The AHP and ANP approaches implicitly include this via their relative nature of rating. The advantage of the SMART technique over AHP and ANP is the fact that the decision making model is developed independent of the alternatives. Therefore the scoring of the alternatives is not relative and therefore introduction of new alternatives doesn't affect the ratings of the original ones making it a more flexible and simpler technique [73].

IV. Case-based Reasoning (CBR)

In CBR, problem solving is done basing judgement on similar past problems and experiences. Basically, the decision is made basing on what has happened before. For example a mechanic fixing a machine having a breakdown that he has been seen before will not have to rate various solutions but rather to employ the similar technique that he employed in the previous scenario [74].

2.4.1.2 Technology Identification, Evaluation, and Selection (TIES) Method

In this method of Technology Selection, decisions are made based on time, budget as well as benefit. The method was a development of the Aerospace Systems Design Laboratory (ASDL) in Georgia U.S.A to address the decision making process for situations whenever there was required intellectual interventions for a failing norm in existing technologies as a result of a dynamic environment. The method is hence rapid, efficient and versatile and therefore it can be easily adopted for various applications. It also helps with cost and time reduction that are essential for the development of new technologies while simultaneously providing measurable justifications for technology selection decisions [75].

2.4.1.3 Scenario Method Using Grey Statistics

This approach is used for decision problems that exhibit high future variability coupled with inadequate data from the past for reference especially if public sector is involved. The method suggests strategic proposals and not decisions by involving the stakeholders whose opinions are sought to give grey statistics that are later fed into modelled scenarios to simulate solutions. Precisely, the method follows the steps as in Figure 7 [76].

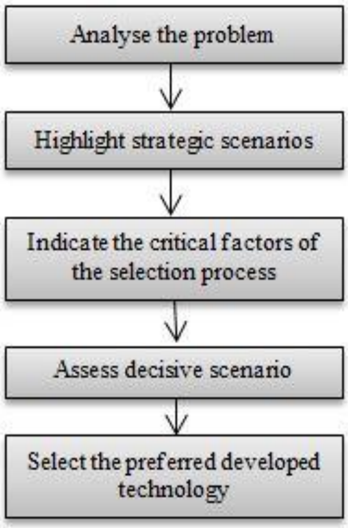

Figure 7: The scenario method of technology selection using grey statistics

2.4.1.4 Marginal Analysis Guided Technology Evaluation and Selection

This is an Early Stage Technology (EST) evaluation method used specifically for selection of technology whose future is uncertain and not yet well studied. The decision makers rely on the information and knowledge from previous experiences to support future project evaluation and selection. The technology evaluation model is built in a way that it can easily adapt to any likely changes of the business environment. The method aims to capture and reapply existing knowledge and experiences of previous projects to evaluate future decision problems. In addition, the method takes an effort at adapting to current trends to respond to the problem at hand [77].

Previous applications of technology selection as a decision support (DS) tool include; Kuria and Maringa [78] applied a scale of 1-10 to score three (3) anaerobic biodigester models to make the most preferred choice of alternative based on a list of selection criteria for small scale biogas units. The study compared the fixed dome, floating drum and flexible bag digesters, and the floating drum model scored highest. However, the study did not consider the relative importance of each selection criteria; it assumed that all criteria were of equal importance. In addition, the three models considered in the study were rather generic compared to the models currently on the market worldwide that possess design specifics. Karagiannidis and Perkoulidis

[79] used MCDA as a DS tool via the Electre III technique to choose the most preferred biogas digester technology from five (5) models for the anaerobic digestion of OFMSW. The study showed that MCDA techniques are practical and reliable for the assessment and selection of AD technology.

2.4.2 Site Selection Techniques

To make decisions on the most preferred locations for siting industrial plants, various techniques have been adopted to aid the location selection process. Among the popular approaches are; the centre of gravity method, Factor rating method, the load distance method and breakeven analyses among others [80].

2.4.2.1 Factor Rating Method

Similar to multi-criteria decision analysis, the factor rating method of site selection uses important location factors such as available space, environmental impact, distances from material sources among others to make analyses that yield the most preferred choice of site. The process can be summarised in the steps below [80-82];

a. Identify and build a list of all important selection factors,
b. Assign a rating to each factor basing on its relevancy to meeting the intended objective. The ratings are given values on scale of 0 to 1 and ensuring that the total of all ratings equals one (1),
c. Assign scores to each alternative location basing on how it performs against each selection factor. The scores are also rational values by the decision maker based on the 0 to 1 scale as in (b) above. The alternative that satisfies a given factor in the best possible way scores highest and the reverse is also true. For a given factor, the total score of the alternative should sum up to one (1),
d. Compute the ranks of the individual alternatives per factor as products of the factor ratings and the scores of the alternatives per respective selection factor,

e. Then finally sum up the products of each alternative obtained in (d) above and the make the choice of the most preferred location basing on the one with the highest total score.

2.4.2.2 The Centre of Gravity (COG) Method

The COG technique is primarily applies the concept of distance and cost. It considers the proposed plant locations vis-à-vis the proposed markets to be supplied, the quantity of products to be moved as well as the associated cost of transportation so as to come to the conclusion of the single optimal location [80]. By using the COG approach, the distance between the plant and its supply market is assigned a weighting factor basing on the quantity supplied that is often expressed as the population of the target market or the total overall tonnage of goods supplied among other forms. The most preferred location also herein referred to as the COG is that site that will give the least weighted distance. As a first step, the alternative locations are placed on a coordinate system with an assumed origin as well as scale to act as references. The decision maker however needs to ensure consistency in the scales and the relative representation of the linear distances. In the event that the volume of goods to be transported to each alternative is the same, the COG is computed by simply obtaining the mean values of the x and y coordinates whereas if the quantities to be transported per location differ, a weighted mean is applied [83]. The COG is computed by the use of the equations 6 and 7 below [80];

$$L_x = \frac{\sum C_{ax} . W_a}{\sum W_a} \quad (6)$$

$$L_y = \frac{\sum C_{ay} . W_a}{\sum W_a} \quad (7)$$

Where;

L_x is the *x* coordinate of the COG,

L_y is the *y* coordinate of the COG,

C_{ax} is the *x* coordinate of site a,

C_{ay} is the y coordinate of site a,

And w_a is the weight corresponding to site a.

2.4.2.3 Load-distance Method

Derived from the COG technique, the load-distance approach applies the principles of mathematics to evaluate alternative locations on the basis of proximity factors. The model is designed with the aim of selecting the most suitable location basing on that site that will give the least total weighted loads leaving and entering the proposed facility. Distances are obtained by assigning coordinates to the specified points of delivery or material sources basing on consistent systems like a grid network on a map. Alternatively distances can be expressed in terms of travel times for the same approach. For example, in the case of a biogas plant, the major concerns will be the haulage distances of the feedstock materials, the sum of the products of the weights and distance gives the overall rank of the site. The site with the smallest sum is the preferred site [80, 84].

2.4.2.4 Breakeven Analysis

This approach employs location economics. It aims to obtain the site that will give the shortest breakeven period. The method computes the costs incurred in setting up the plant at a particular site and then evaluates the associated breakeven periods based on the envisaged benefits and revenues. The site which gives the shortest breakeven period is the preferred choice [80, 84].

Previous applications of site selection as a decision support (DS) tool include; Ma et al. [85] employed the AHP technique of MCDA to ascertain the relative importance of site selection criteria in an effort to develop a geographical information system (GIS) based model for siting farm-based centralised AD systems in Tompkins County, New York, U.S.A. The study employed MCDA in combination with GIS based approaches.

Despite the several examples of MCDA applications for AD systems, there has been no such previous area specific study applied for the South African environment which has up to now faced challenges in the implementation of AD systems. This study presents the results of applying MCDA techniques for supporting decisions on the selection of the most suitable biogas technology for the waste-to-energy UJ-SANEDI project, and the choice of the most preferred site on the UJ DFC campus for installing the proposed biogas digesters.

CHAPTER: MATERIALS AND METHODS

3.1 Introduction

This chapter describes the methodology that was used in the study and covers the step by step approaches carried out to achieve the specific objectives of the research and ultimately the general objective.

3.2 Feedstock Analysis

The design of an anaerobic digestion system for biogas production is primarily governed by both the qualitative and quantitative properties of the substrate to be digested. Therefore, the assessment of the feedstock properties is the most important step in the system design. Data obtained from these analyses provides essential input parameters for determining the likely volume of biogas to be harvested from the system, its composition as well as the energy value. The analysis also provides essential inputs like the waste generation rates for sizing of the anaerobic biodigester. In this study, the analysis was divided into feedstock quantification, characterisation and biomethane potential.

3.2.1 Feedstock Quantification

The waste generated at the study area was quantified over two (2) seasons (autumn and spring) using the measurement at point of collection approach because of its level of accuracy and owing to the fact that there were no reliable and satisfactory existing data. In applying this approach, the procedure below was followed;

3.2.1.1 Definition of Waste Stream Categories

As a first step, the waste was defined according to categories. Basing on the current existing waste management system, the solid waste stream at UJ DFC was divided into general waste (residential) and garden waste. The garden waste was further broken into compostable and none-compostable. The general waste was divided into recyclable (usable glass, metals, tins etc.) and non-recyclable. Then non-recyclables were divided into biodegradable and non-biodegradable. The target component for the waste-to-energy project was the biodegradable portion of the non-recyclable general waste as well as the compostable portion of the garden waste. These are as shown in Figure 9.

3.2.1.2 Weighing for Category Quantification

Following the existing waste sorting criteria at the waste transfer station (WTS) for the general waste, the waste was weighed fresh from source before sorting to obtain the total amount of waste. The recyclable component of the waste from the collection bags was sorted out first. These would then be re-weighed to obtain the total non-recyclables and then sorted further into the biodegradable and the uncategorised whose weights were also obtained accordingly.

At the garden waste station, the total weight of the garden waste was also obtained first and then the compostable garden waste was sorted from the non-compostable and their weights obtained accordingly. From step 1 and 2, the total of the biodegradable fraction of the waste were computed from the total of the biodegradable non-recyclable general waste and the compostable portion of garden waste. To execute the waste quantification exercise, the following equipment were required: waste bins and bags, shovels, weighing scale, rakes and Personnel Protective Equipment (PPE) such as hand gloves, coveralls, safety boots, nose masks and safety glasses among others.

3.2.1.3 Timing

The exercises were conducted at randomly selected week days during which waste sorting takes place at the respective transfer stations for at least a month both during the spring and autumn seasons to carter for seasonal variation. The two seasons were selected because they took care of the extremes of waste generation at the study area throughout the year. The data obtained was averaged to obtain the daily waste generation rates.

3.2.1.4 Sampling and Statistical Analysis

The exercises were conducted such that all the available waste generated from the previous day was weighed and sorted at the current date of sorting. To test the reliability of the obtained data, analysis for obtained means was undertaken to ascertain whether they are at least within 90% confidence interval of their standard deviations as specified by UNEP standards for sampling of municipal solid waste [55].

3.2.2 Feedstock Characterisation

For evaluation of the OFMSW as a feedstock for energy recovery, the waste had to undergo various selected tests to obtain key performance parameters. The tests that were conducted were; ultimate elemental analysis, in-situ density, volatile solids (VS) content, moisture content and total solids (TS) content.

The samples to be used in the laboratory analysis were obtained from the same source in a similar way from the waste quantification exercise. The samples were manually mixed and reduced to manageable sizes using the conning and quartering method of sample preparation in accordance to BS EN 14899:2005. The samples were then wrapped in air tight plastic bags. Instantly, a small portion of the freshly obtained samples was measured for in-situ density and moisture content tested before destabilisation. The balance of the sample was preserved in a fridge for further tests. Prior to all conducted tests, the samples were ground using a blender to achieve a uniform substrate. The procedures for the various tests conducted are as below;

3.2.2.1 In-situ Density

The wet density of the feedstock was determined in the field using containers of known volume and the weighing scale. From the fresh sample, the waste was loosely packed in a 250 ml container of known mass (m_c) and then the mass of the container plus sample (m_{c+s}) was obtained on the scale from which the density would be computed as in equation 8. The procedure was carried out on four samples and the average value obtained as the density of the waste.

Density of Sample;

$$(d_s) = (m_{c+s} - m_c)/250 \text{ ml} \quad (8)$$

3.2.2.2 Total Solids and Moisture Content

Freshly ground samples were taken to the laboratory for moisture content determination. For each aliquot, 33 g of sample was measured off the larger sample and oven dried at 105°C for 24 hours. The dishes and watch glasses to be used in the experiment were first oven heated at 105°C for 1 hour and later cooled in a desiccator to ensure that they are moisture free prior to use. The combined mass of the dish and watch glass (m_d) was obtained first after the desiccation procedure. Then the approximately 33 g fresh sample was placed in the dishes, spread out and covered with watch glasses. Then the mass of the arrangement (m_s) obtained. The sample was then placed in the oven and dried for 24 hours at 105°C after which it was cooled in a desiccator and reweighed to obtain the new mass of dry sample (m_{sd}). The final value of msd was obtained after repeated 1-hour heating, cooling and weighing process that yielded negligible change in mass. From these, the total solids and moisture content were computed as in equations 9 and 10;

$$\% \text{ total solids (TS)} = (m_{sd} - m_d)/(m_s - m_d) * 100 \quad (9)$$

$$\% \text{ moisture content (MC)} = (m_s - m_{sd})/(m_s - m_d) * 100 \quad (10)$$

3.2.2.3 Volatile and Fixed Solids Content

The residue obtained from the total solids and moisture content determination was then heated in a furnace at 550°C for 2 hours and the new weight of the sample with the dish was obtained as the mass of residue without volatile solids (m_r). Necessary precautions were taken to ensure a moisture free furnace. From these, volatile and fixed Solids content were computed as in equations 11 and 12;

$$\% \text{ volatile solids content (VS)} = (m_{sd} - m_r)/(m_{sd} - m_d) * 100 \qquad (11)$$

$$\% \text{ fixed solids (FS)} = (m_r - m_d)/(m_{sd} - m_d) * 100 \qquad (12)$$

3.2.2.4 Ultimate Analysis

To obtain the elemental (CHNOS) composition of the feedstock, the testing was outsourced to a specialist laboratory as the department lacked an elemental analyser. Part of the earlier prepared sample was delivered to the laboratory and the test was carried out at an agreed cost.

3.2.3 Feedstock Bio-methane Potential

In order to give an estimate of the biogas production rates of the intended feedstock, 4 bench-scale anaerobic batch digesters were set up at pre-set optimum conditions of temperature, and pH. From literature, the optimum operating pH range for anaerobic digestion is 7 to 8 and the mesophilic temperature range is 30 to 40°C, therefore the temperatures were fixed at 35°C [10, 26].

3.2.3.1 Procedure

The setup was made up of four (4) bench-scale batch digesters with working volumes of 5L connected to rubber delivery tubing and securely sealed off with silicon glue to ensure air tightness. The tubes were run into inverted graduated measuring cylinders immersed in water from which gas levels were read applying the principle of downward displacement.

To inoculate the substrate, 50 g of cow dung were digested first in a separate set up for 14 days until little or no biogas was produced. The waste water from this set up was then used to inoculate the feedstock.

The feedstock was ground using a blender to ensure a homogeneous substrate and reduced particle sizes. 150 g of this was then added to 2 litres of fresh water and 2 litres of inoculated waste water to form 4 litres of slurry which was then poured into the digesters. It was further pre-treated by the addition of an 8% solution of sodium hydroxide (NaOH) prepared by adding 8 g of NaOH to 100 ml of water to ensure pH levels in the range of 7-8 so as to counter the effect of the volatile fatty acids (VFAs) accumulation from the food waste. Temperature regulation was ensured by immersing the digester bottles into an automatic electric water bath set at 35°C.

The contents of the digester bottles were shaken regularly to ensure uniform mixing of the substrate. The pH was also continuously monitored using a pH meter to ensure values within the optimum range. The bottles were further manually squeezed to get rid of any trapped air in the remaining 1L space for gas-holding prior to commencement of the setup. Figure 8 shows the laboratory scale set up of the anaerobic biodigesters.

Figure 8: Anaerobic digestion setup

The gas produced was sampled using a gas sampling syringe and then transferred to a gas chromatograph (GC) for analysis. The methane content of the biogas was measured using a GC with flame-ionization (FID) and thermal-conductivity detectors (TCD) with operating conditions of oven temperature 70˚C, detector 150˚C and injection port 80˚C. Helium was used as the carrier gas (20 ml/min). This analysis would then give an indication of the various compositions of the biogas and their relative percentages which would later guide on the energy value of the produced gas from the system.

3.3 System Design

Implementation of an anaerobic biogas digester system for municipal solid waste in a built-up urban environment presents a set of complex factors that have to be analysed carefully before informed decisions can be made. Factors such as available space, economic feasibility and the safety considerations of the system among others present unique challenges that have to be studied carefully. The design of the system used key input data obtained from the feedstock analyses and it was broken into digester sizing, plant model and site selection as well as system integration.

3.3.1 Biogas Digester Sizing

Using the obtained values from the waste quantification and characterisation exercises, appropriate input parameters like the feedstock volumetric flow rate were ascertained that aided the bioreactor design using mathematical models as in equations 13 to 15;

Volume of reactor

$$V_r = \text{Feedstock volumetric flow rate (Q) x HRT} \quad (13)$$

Where;

HRT is the hydraulic retention time in days.

Taking the volume of the gas holder to be half the reactor volume;

Volume of the gas holder

$$V_g = V_r/2 \quad (14)$$

Total biodigester volume (V_d) is the sum of the reactor and the gasholder volumes.

$$V_d = V_r + V_g \quad (15)$$

The feedstock volumetric flow rate was obtained as the volume of the daily waste generated in addition to the required amount of water to achieve the desired fluidity of 85% moisture content. To check the adequacy of the obtained digester capacity, a comparison was made of the computed OLR based on the reactor volume against the prescribed value for OFMSW which ranges between 5-10 kgVS/m^3 from literature [36].

3.3.2 Plant model and site selection

In this study, both site and technology selections for the proposed biogas digester were done via multi-criteria decision analysis (MCDA) techniques owing to their robustness and simplicity as well as the fact that the selection criteria were obtainable and measurable at the same time.

3.3.2.1 Digester Model Selection

The SMART technique of MCDA was used to analyse the various biodigester models owing to the fact that all their attributes were directly measurable and non-subjective. In addition, the SMART technique supports the evaluation of an elastic set of alternatives, which makes it better suited for constantly changing sets of variables such as supplier lists, unlike other MCDA techniques such as AHP and ANP. In applying SMART to select the most preferred biogas digester model, the steps below were followed;

- Identification of the goals/objectives; the objective of the analysis was to make a decision on what the most preferred biogas plant was for the project under consideration,
- Listing of potential alternatives; a list was developed of the biogas digesters available on the market herein also referred to as the alternatives from which a choice would be made.
- A list of selection criteria was built basing on factors that are considered for selection of a biogas plant. Such factors include temperature regulation abilities, local availability, ease of construction and study specific factors such as the plant’s suitability to treat OFMSW.

- Creation of a unified weighting scale for the set criteria basing on their level of importance. The criteria were then assigned weights ranging between 0 to1. Unifying the weights implies that the summation of all weights equals 1:

$$\sum_{i=1}^{n} W_i = 1 \qquad (16)$$

Where;

W_i is the unified weight of criteria i.

Weights of corresponding criteria are also listed in Table 10 alongside justifications for their corresponding values.

- Assignment of scores to individual alternatives depending on how they score on the set criteria ranging from 0 to 1.
- Computation of the weighted ranks (R) of individual alternatives as a sum of the product of scores and attribute/factor weights:

$$\sum_{i=1}^{n} W_i S_1 = R_1 \qquad (17)$$

Where;

R_1 is the rank of alternative 1,

And S_1 is the score of alternative 1 with regards to criteria i.

- Then finally, a decision was made on the most preferred digester basing on one with the highest rank. Details of the ranking according to corresponding aggregate scores of alternatives as shown in Table 11.

3.3.2.2 Site Selection

For site selection, the weighted factor rating (WFR) technique was used in combination with the AHP approach of MCDA. The weights of the various factors and alternatives were obtained using the AHP technique of MCDA owing to its ability to include pair-wise comparisons of the alternatives as well as the criteria to emphasise relative importance and independence of the alternatives. This gives a more accurate result for comparison of spatial data. The procedure followed was as below:

- Identification of the goal/objective: the objective of the analysis was to make a decision on what the most preferred site was for siting a biogas plant around the UJ Doornfontein Campus,
- Choice of alternatives: preliminary surveys guided by stakeholder meetings were conducted around the school campus in search for potential alternatives. This yielded a total of three (3) locations on which detailed studies and analyses were undertaken to make the choice of the most preferred site. That is, the site near the existing waste transfer station (WTS), near the students' centre (SC) and finally next to Aurum Ladies Residence (AR). A list of these and their attributes is presented in Table 12. The relative locations of the 3 sites at the UJ DFC campus, taken using Google maps' satellite image, is shown in Figure 14.
- Choice of selection criteria: a list of factors herein referred to as the criteria was made against which the sites would be scored. These included among others the available area at the site and distance from feedstock source. Details of these are given in Table 13.
- Using the AHP fundamental scale of scores 1-9 as showed in Table 4, pairwise comparisons of the alternatives were made with regards to each criterion using a programed Microsoft excel sheet. These would finally yield priorities of the alternatives with respect to a particular criterion. Using the same scale, pairwise comparisons were made for the various criteria against each other as well basing on how well they satisfy the set objective and their relative priorities obtained,
- Total aggregate priorities were obtained as sums of the products of the individual priorities of alternatives and criteria. For alternative A whose priorities according to

criteria 1, 2, 3 and n are P_{a1}, P_{a2}, P_{a3} and P_{an}, its aggregate score S_a is given by the equation 18;

$$S_a = [p_I(P_{a1}) + p_{II}(P_{a2}) + p_{III}(P_{a3}) + p_n(P_{an})] \quad (18)$$

Wherep_I,p_{II}, p_{III} and p_n are the relative priorities of the criteria 1, 2, 3 and n..

- Then finally, the decision on the most preferred site basing on one with the highest score was made.

3.3.3 System Set-up, Integration and General Assessments

After reactor design and selection, the various accessories necessary for the entire system to run were designed, selected and integrated. Then costs and energy requirements of the various components were assessed from the respective suppliers. This in turn gave parameters for analyses such as assessment of the system energy usage and economic analysis. Furthermore, considerations were made for safety precautions during the operation of the system.

3.3.3.1 Energy Usage Assessment

Based on the power ratings of the various system components as obtained from the supplier catalogues, the total energy consumption of the system was evaluated. In addition, from the biogas production rates obtained using the biomethane potential tests on the feedstock as well as the feedstock generation rates, an evaluation was made of how much energy the system was capable of producing from biogas production. As a result, an energy usage assessment was then undertaken comparing the energy produced by the system against the energy consumed. This would then give an indication on the feasibility of the project as a whole [45].

3.3.3.2 Economic Analysis

Using the results from the overall costing of the integrated system, a detailed economic analysis of the system was undertaken based on economic performance indicators such as the project's net present value (NPV), cost-benefit ratio (BCR) and internal rate of return (IRR) over a pre-selected economic period using the prevailing central bank lending rate as the discounting rate.

The present value (PV) is the estimated money value in future after discounting using a factor known as a discounting rate to reflect its value currently. This value is always equal or less than its value in future because the idea is for the money to earn interest over time also referred to as its time value. Hence, the NPV is the aggregate sum of the present values of a given project's cash flows over the project's economic period. The NPV gives an indication on the value addition capability of the project to the investor, a positive value of NPV indicates a financially viable investment and a negative value shows economic failure. As a decision making tool, NPV can be used to choose amongst all seemingly viable projects by choosing one with the highest NPV. The IRR on the other hand is a discounting rate that yields an NPV value of zero. An IRR value greater than the prevailing lending rate on the money markets indicates a viable project and the higher the value, the more desirable it is to invest in the project. The BCR is the ratio of the project's benefits against the costs expressed as discounted present values in monetary terms. A BCR value greater than 1 indicates an economically viable project and the higher the value the more desirable the investment [86, 87].

The analyses were carried out using a programmed Microsoft excel sheet and standard formulae as showed in equations 19 to 22.

$$NPV = \frac{Estimated\ Net\ Future\ Value\ (NFV) in\ 20\ years}{(1+r)^n} \quad (19)$$

$$NPV = \sum_{n=1}^{n=t} \frac{NFV}{(1+r)^n} \quad (20)$$

$$IRR = \sum_{n=1}^{n=t} \frac{NFV}{(1+r)^n} = 0 \quad (21)$$

$$BCR = \frac{Net\ Benefit}{Net\ Cost} \quad (22)$$

Where r is the discounting rate expressed as a percentage and n is the duration of the project in years. For these analyses, the assumptions below were made;

- The useful economic life of the project was assumed to be 20 years owing to the fact any benefits or costs that are accrued after the 20th year would be significantly small when discounted to the present worth,
- The discounting rate was taken as 9% as given by the South African central reserve bank [88],
- The salvage value of the biogas digester was excluded from the benefit stream since after the 20th year of operation, the digester is assumed have zero value,
- The land for establishment of the project belongs to the user hence no cost has been included for space requirements,
- Benefits from selling carbon credits were assumed to be insignificant.

Basing on the results obtained from the economic analysis, conclusions were then drawn on the project's overall economic viability.

3.3.3.3 Health and Safety

By assessing the health and safety standards of the plant, the various hazards associated with the setting up, operation and maintenance of anaerobic digestion systems for biogas production were identified. Then, their corresponding remedial measures were devised and incorporated into the plant design as well as operation and maintenance plans.

CHAPTER 4: RESULTS AND DISCUSSION - FEEDSTOCK ANALYSIS

4.1 Introduction

This section presents and discusses the results obtained from the feedstock analyses undertaken. These include quantification studies, characterisation and biomethane potential studies. It is from these results that key design parameters would be obtained for the system design.

4.2 Feedstock Quantification

Prior to the waste quantification exercise, the waste was broken down into waste stream categories. These are as showed in Figure 9. Table 5 shows the summary of the results obtained from the waste quantification exercises over the spring season that runs from September to November as well as the autumn from March to May. Figure 10 and Figure 11 show the various proportions expressed as percentages of the individual waste streams.

Approximately, 378 kg of municipal solid waste was generated daily at the campus of which 231.22 kg (61.2%) was the OFMSW portion made up of food waste and compostable garden waste. Of the total waste generated, 64.6% and 35.4% were the general waste and the garden waste, respectively. The food waste accounts for 47% of the general waste generated whereas 26%, 5.2% and 2.1% were recyclables, paper bags and polystyrene, respectively. And, the remaining 19.7%, is made up of a complex mixture of substances that were referred to as un-categorised in this study. Around 86.7% of the garden waste was compostable and the balance was non-compostable. More garden waste was generated during the autumn season than spring due to the higher tendency of leaves to drop off trees during autumn. However, there was a higher percentage of non-compostable garden waste in relation to the seasonal total for garden waste during the autumn season than during the spring because most of the garden waste produced in autumn is not fresh green waste but rather dry sticks.

Table 5: Average waste generation rates per day at UJ DFC

	Waste Stream	Spring		Autumn		
		Mean (kg)	Standard Deviation (kg)	Mean (kg)	Standard Deviation (kg)	Combined mean (kg)
General waste	Recyclables	44.292	±5.213	82.297	±42.444	63.295
	Paper bags	22.260	±19.857	3.064	±0.830	12.662
	Food	134.487	±21.767	95.603	±17.897	115.045
	Polystyrene	3.628	±0.842	6.788	±2.947	5.208
	Uncategorised	35.782	±5.979	60.014	±19.696	47.898
Garden Waste	Compostable garden waste	98.799	±14.841	133.560	±34.917	116.179
	None Compostable garden waste	7.803	±1.835	27.876	±9.908	17.839
TOTAL		347		409		378

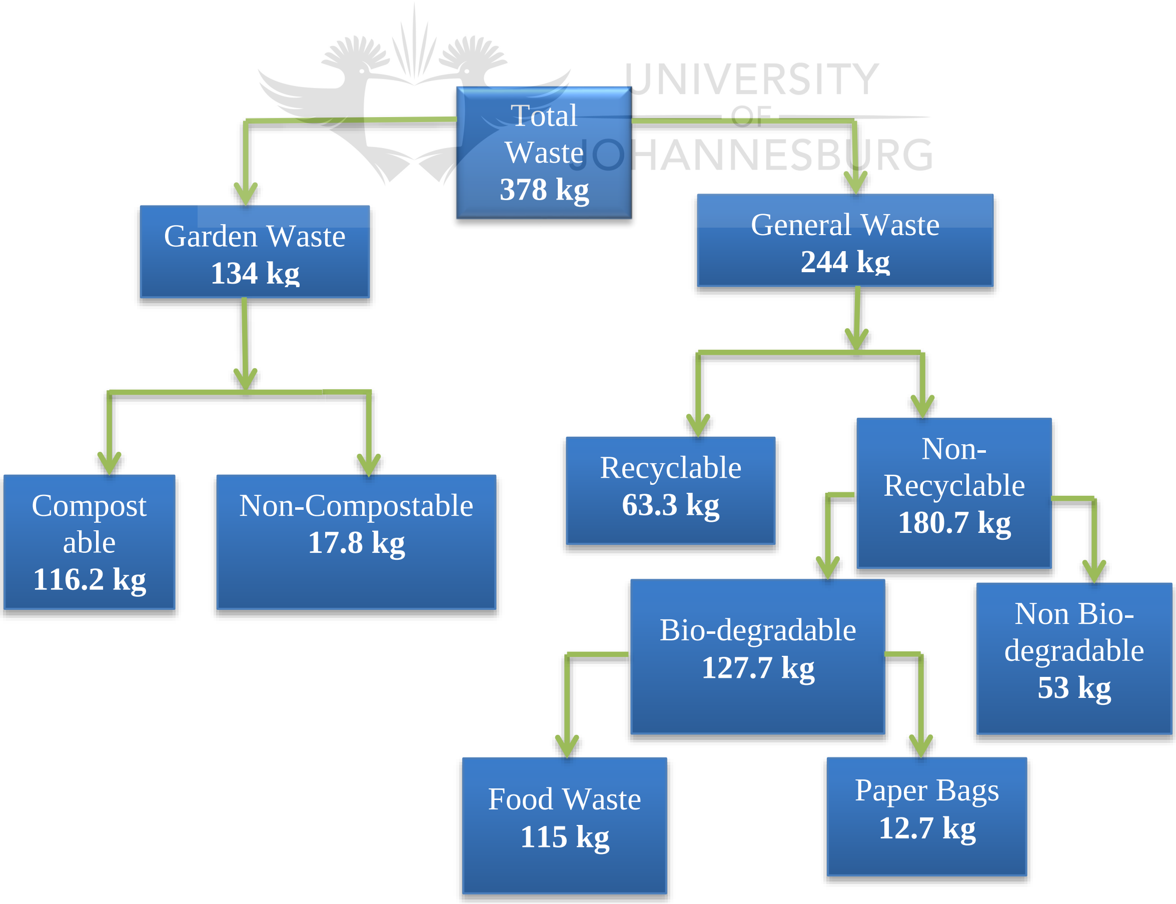

Figure 9: Daily waste generation and categories for UJ DFC

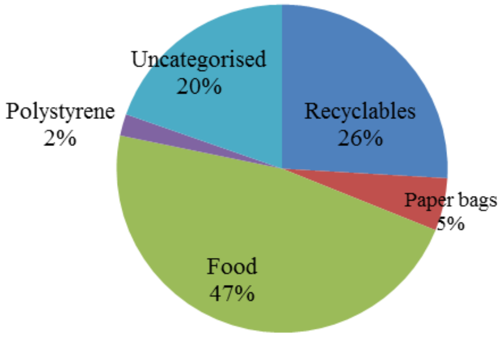

Figure 10: Daily general waste per category

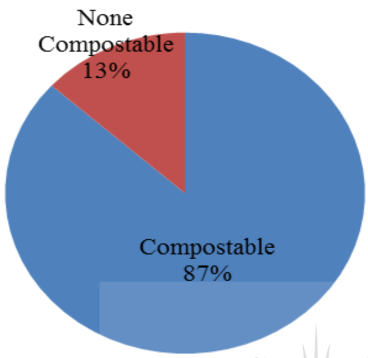

Figure 11: Daily garden waste per category

4.3 Feedstock Characterisation

Table 6 highlights key parameters of the feedstock that were obtained from the laboratory analyses. These would essentially be used for the design of the AD system. The waste was found to contain 27.14% solids and 72.86% moisture. In addition, of the total solids, 94.9% was volatile solids and the remaining 5.1% was ash. The density of the fresh waste was recorded to be 775 kg/m^3. Generally, the OFMSW characteristics obtained were in agreement with most of the reviewed literature which indicate that typical OFMSW has TS and VS ranges of 20-30% and 90-95%, respectively [37-39, 41]. And, the C/N ratio of 25:1 obtained was within the optimum range of 20-30:1 [37-39, 41].

From section 4.1, the rate of OFMSW generation was 231.22 kg per day. With a density of 775.0 kg/m^3, the volumetric flow rate of the feedstock was hence approximately 0.3 m^3 per day. Adding an equal amount of water to achieve the desired working fluidity, the design feedstock volumetric inflow was computed as 0.6 m^3 per day.

Table 6: Summary of feedstock characteristics

Parameter	Value
Average daily generation rate	231.22 kg/day
Total Solids (TS)	27.14%
Moisture Content (MC)	72.86%
Volatile Solids (VS) (% of TS)	94.90%
Fixed Solids (FS) (% of TS)	5.10%
Density	775.0 kg/m^3
C,H,O,N	52.8%, 6.02%, 38.42%, 2.1%
C:N ratio	25:1

4.4 Feedstock Biomethane Potential

Figure 12 shows the corresponding plots of the volumetric biogas yield from the four (4) individual bench-scale batch digesters against digestion time and Figure 13 on the other hand shows the combined average biogas yield against digestion time of the four batch tests. The maximum estimated average biogas yield was 14 931 ml from the 150 g sample. Considering the feedstock characteristics from Table 6 and the sample size of 150 g, the average specific biogas yield of the feedstock was obtained as 386.46 ml/gVS.

The rate of biogas generation increased with time from 0 to 8 days, with the peak rates obtained at day 2. The production rates started to reduce thereafter and eventually flattened out from day 14 through 21. Over 95% of the biogas yield had been achieved by day 14. The onset of biogas production began sooner as a result of the particle size reduction by grinding the substrate as well as ready inoculum. The obtained value of 386.46 ml/g VS from this study agrees with most reviewed literatures on production of biogas from OFMSW which give values between 300 and 400 ml/g VS [12, 41, 42].

The biogas produced had an almost constant methane content. The methane content started at approximately 52% during the first 4 days and steadily increased to 62% on the 8th day and remained constant throughout the digestion period. The average CH_4 and CO_2 contents were measured as 62% and 38%, respectively. From literature, OFMSW as a substrate for biogas production is capable of producing biogas that has 58-70% methane. Hence, the value obtained of 62% is within the expected range. From Table 6, the feedstock was generated at 231.22 kg per day with TS and VS content values of 27.14% and 94.9%, respectively, which gives a VS generation rate of 59.6 kg VS per day. Therefore, the system is capable of producing 23.014 m^3 of biogas per day at 62% methane content.

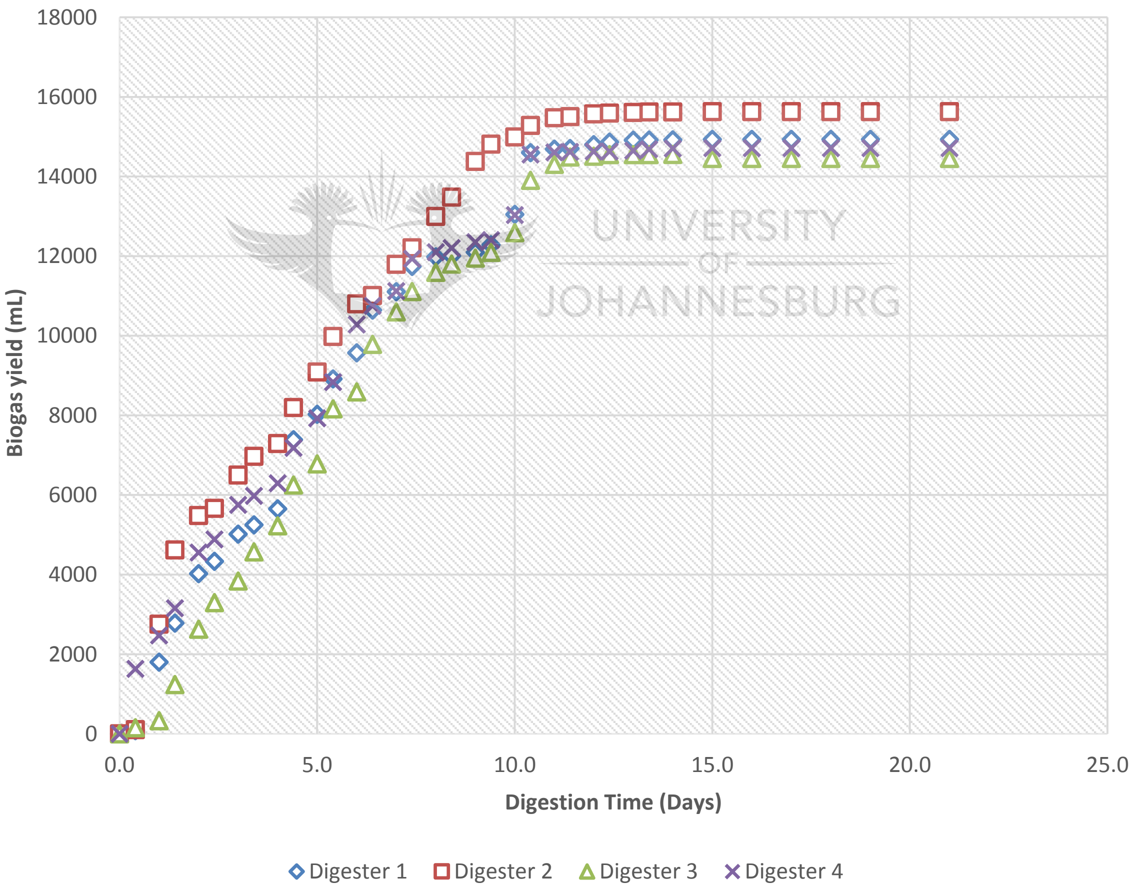

Figure 12: Plot of biogas yield against time from the anaerobic digestion of OFMSW

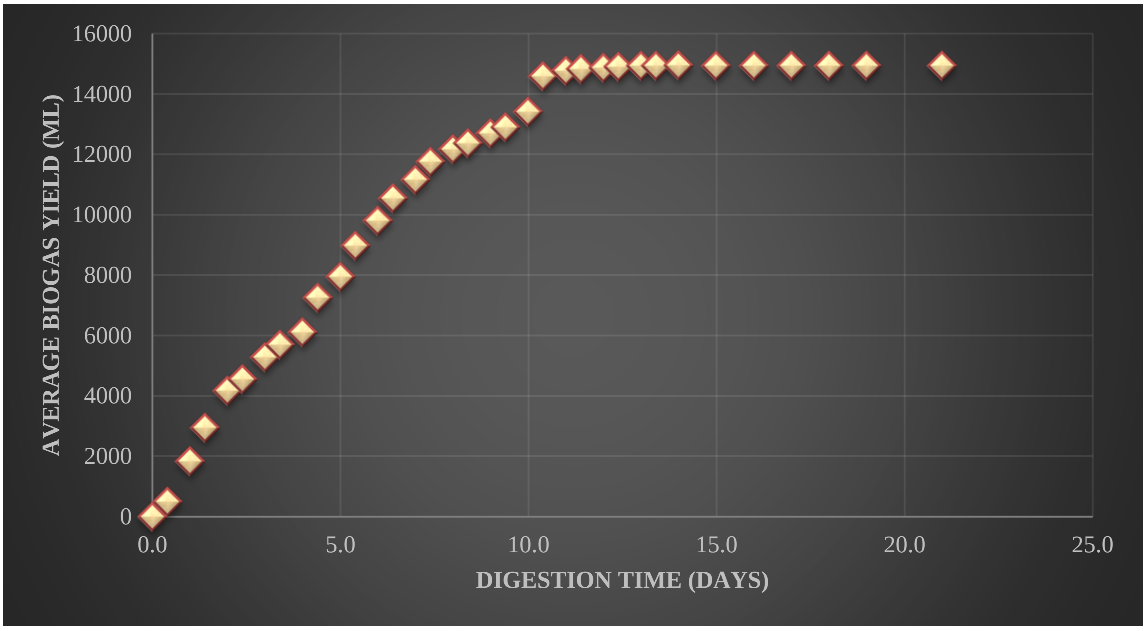

Figure 13: Average biogas yield against digestion time

A study by Wan et al [89] showed that the co-digestion of food waste with grass generally stabilises the AD process in single stage anaerobic reactors by improving nutrient and pH balance as opposed to the exclusive use of food waste as sole feedstock. This was the case for the target feedstock since it was a mixture of food and garden waste. However, it was observed that pH values would over time slightly drop towards the acidic range calling for the addition of an 8% solution of sodium hydroxide to balance to the optimum desired range. Hence, the feedstock should be pre-mixed with an alkaline additive such as baking soda ($NaHCO_3$) so as to ensure optimum range of operational pH. However, care should be taken not to exceed the sodium toxicity range of concentrations greater than 3,500 mg/l. At a flow rate of 0.6 m^3 per day, the feedstock would require an estimated 1 kg of alkali additive. For optimal performance, the temperature must be maintained within the desired range of 30 to 40°C and the substrate must be agitated regularly.

CHAPTER 5: RESULTS AND DISCUSSION - SYSTEM DESIGN

5.1 Plant Sizing

Using the results obtained from the feedstock analysis and literature, the appropriate size of the biogas digester was determined using standard procedure considering feedstock quality and quantity. Substituting the design parameters into equations 13 to 15, the digester capacity was obtained as 27 m^3 but further rounded up to 30 m^3. The obtained digester capacity gave an organic loading rate of 6.65 kgVS/m^3 which is within the acceptable range of 5-10 kgVS/m^3 implying that it was adequate [36]. A breakdown of the results is as shown in Table 8. The feedstock design parameters are as shown in Table 7.

Table 7: Feedstock design parameters

Parameter	Value
Feedstock volumetric flow rate	0.6 m^3/day
Total Solids (TS)	27.14%
Volatile Solids (VS) (% of TS)	94.90%
Optimum Hydraulic retention time (HRT)	25-30 days [12]
Optimum Organic loading rate	5-10 kgVS/m^3 [36]

Table 8: Biogas digester sizing

Parameter	Value
Reactor size (V_r) (Taking the HRT of 30 days)	18 m^3
Organic loading rate	6.65 kgVS/m^3
Gas holder size (V_g)	9 m^3
Biogas Digester Volume (V_d)	27 m^3 ≈ **30** m^3

5.2 Digester Model and Site Selection

5.2.1 Model Selection

5.2.1.1 Potential Alternatives

Using MCDA techniques, a suitable biogas model was selected from a list of potential alternatives as showed in the subsequent sections. The developed list of biogas digesters alongside a summary of their attributes is presented in Table 9.

5.2.1.2 Selection Criteria

Table 10 presents a list of set criteria for the selection of the various biogas digester technologies. The same table gives the unified weights of each individual criteria followed by a detailed justification for the choice of weight.

Table 9: A list of potential technologies of biogas digesters and their specifications

Model	A	B	C	D	E	F	G	H
Agama Pro 6	BiogasPro S.A	6 max	Yes	45	Buried Underground	Polyfibre Tank	South Africa	Manual
Puxin	BiogasSA	10 max	Yes	60	Buried Underground	In-situ Concrete	China/ South Africa	Hydraulic
Bio4gas	IBERT	From 200	Yes	600	Incorporated CHP generator	In-situ Concrete	Germany/ South Africa	Incorporated
GREENBOX	AEPS	From 100	Yes	1,200	Insulated	On-site steel	Germany/ South Africa	Incorporated
Geo membrane	Biotech	35	Yes	180	None	Polyfibre tank	India	Manual
WELTEC	Weltec	2,500	Yes	25,000	Incorporated	Stainless Steel	Germany	Incorporated
PVC Portable digester	Chongqing Biogas New Energy Co.	10	NO	10	Buried underground	Concrete	Chongqing, China	None
ÖKOBIT	ÖKOBIT	2,500	Yes	20,000	Incorporated	Stainless Steel	Germany	Incorporated
BioConstruct	BioConstruct	2,400	Yes	21,000	Incorporated	In-situ concrete	Germany	Incorporated
BITECO	BITECO	600	Yes	4,980	Incorporated	In-situ concrete	Italy	Incorporated
STANDARD	BIODIGEST ER	30	NO	210	Insulated	Polyfibre tank	England	External Hydraulic System
Food Waste Biodigester SR100	Sunrise-econergyCo. Shenzhen	100	Yes	1,000	Incorporated	enamel sheeting	Guangdong , China	Incorporated
Floating Digester	Sunrise-econergyCo. Shenzhen	60	NO	35	Buried underground	Concrete structure	Schenzen, China	None
Helios® system	UTS Biogastechnik GmbH	From 2000	Yes	15,000	Incorporated	Cast In-situ concrete	Germany	Incorporated

A: Supplier, B: Capacity (m^3), C: Suitability for OFMSW, D: Cost of plant (ZAR 1000), E: Temperature regulation modification, F: Materials, G: Origin, H: Agitation method

The project was fixed at small scale level with OFMSW as a preselected type of feedstock. Therefore, the scalability of the plants and their suitability to handle OFMSW were taken to be the ruling factors for digester selection each having individual weighted factors of 0.2. Next in importance were the relative cost prices of the individual plants and their availabilities locally because both factors had a direct implication on the overall project cost. They weighed 0.17 and 0.18, respectively. Temperature regulation and ease of construction, operation and maintenance both weighed relatively lower at 0.1 because the technologies in consideration were relatively simple, easy to set up and therefore temperature as an operating factor can easily be regulated. The least important factor was the presence of agitation accessories weighing 0.005 since at small scale, biogas digesters can be agitated manually with relative ease.

5.2.1.3 Scores and Ranking

Table 11 represents the summary of the results from the scoring and ranking of the various biogas digesters against the weighted selection criteria. The Puxin digester had balanced attributes scoring well across all criteria despite not being the top scorer at any hence obtaining the overall highest score and therefore the most preferred option for the project. Its attributes' scores are almost similar to the Agama digester owing to the fact it's a locally available technology and an easy one to construct too. However, the technology design has incorporated a hydraulic agitation modification as well as system temperature regulation through its mode of construction since it is a below-ground construction. The Puxin digesters are available in customisable 10 m^3 and 6 m^3 capacities therefore easily scalable for small scale applications. All these factors combined give the Puxin digester a much higher aggregate score compared to the rest of the models under consideration.

The Geo Membrane digester from India's Biotech comes at the lowest cost compared to the rest in the top three technologies hence the high score. It also turns out to be the most flexible to size especially at small scale and the most preferred plant for treatment of OFMSW as well.

However, its downside was the fact that the technology is not available locally and hence, scoring 0.00 in that particular selection criterion dropping its overall total score considerably.

Table 10: Selection criteria with corresponding unified weights for selection of a biogas digester

Attribute	Unified Weights (Wi)	Justification
Cost	0.17	The cost price of any technology to be procured is a very vital factor in the selection process since it dictates the economic viability of the project. An economical choice of technology is the one that will serve the intended objective of the project at the least possible cost. The price of the plant therefore is a strong attribute in the selection process having a weight of 0.17 just 0.01 below local availability at 0.18. The cost of the plant is not a limiting factor unlike others such as the scalability of the technology that are fixed hence not the strongest criterion [65, 79, 90, 91]
Local availability	0.18	Locally available technologies reduce the project costs considerably since there are no extra costs incurred in mobilisation of labour and materials as well as reduced taxes. In addition to lowering project costs, locally available technologies are already understood within the area of application therefore easy to set up and promote the development of local products as well as the economy at large. Therefore local availability is a strong factor and hence carries a strong weight at 0.18 [91, 92].
Capacity scalability	0.2	This is the measure of the ease with which the presented technology can be scaled to the envisaged capacity of the project. This is a very important factor because some plants are only available in particular scales. This is a project limiting factor because in the event that a particular model cannot be sized within the required project scale, it is automatically disqualified therefore having a very strong weight of 0.2 [92].
OFMSW suitability	0.2	The design of anaerobic digestion system for biogas production is primarily governed by both the qualitative and quantitative properties of the substrate to be digested. In this case the substrate to be treated was fixed as OFMSW and therefore the suitability of the given technology to treat this substrate was a project limiting factor hence carries a very strong weight of 0.2 at the same level of importance as the scalability of the plant[5, 10].
Temperature regulation ability	0.1	Anaerobic digestion of biomass by microbes for biogas production occurs optimally at temperature ranges of 30°-40°C. Therefore a techno-efficient biogas plant system should have the ability to regulate its working temperatures within the optimal range otherwise the system can underperform or even fail. However, most systems have laboured to incorporate temperature regulation design modifications making the factor a rather fairly strong one as a selection criterion with a weight of 0.1[5, 26].
Presence of agitation accessory	0.05	The substrate has to be continuously stirred to ensure the even distribution of the anaerobes as well as intimate contact between the anaerobes and the substrate. This eventually improves the AD process since the activity is evenly distributed through the reactor. Most systems have however laboured to incorporate modifications to facilitate substrate agitation making the factor also rather fairly strong as a selection criterion with a weight of 0.05 [26].
Ease of construction, operation and maintenance	0.1	The plant should be easy to construct, operate and maintain to reduce the need for expatriate labour which usually increases the project's overall costs. Most available biogas technology has been simplified for easy set up thereby making the criterion also a rather fairly strong one with a weight of 0.1 [78, 93].

Table 11: Scores against criteria and overall ranks for the alternative biogas digester models

Criteria	A		B		C		D		E		F		G		
Weight	0.17		0.18		0.2		0.2		0.1		0.05		0.1		
Model	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	RANK
Puxin	0.65	0.11	0.85	0.15	0.85	0.17	0.70	0.14	0.50	0.05	0.10	0.01	0.80	0.08	0.709
Agama Pro 6	0.60	0.10	1.00	0.18	0.65	0.13	0.70	0.14	0.10	0.01	0.10	0.01	1.00	0.10	0.667
Geo membrane	0.80	0.14	0.00	0.00	1.00	0.20	0.90	0.18	0.30	0.03	0.30	0.02	0.70	0.07	0.631
Bio4gas	0.75	0.13	0.70	0.13	0.00	0.00	0.80	0.16	1.00	0.10	1.00	0.05	0.50	0.05	0.614
GREENBOX	0.20	0.03	0.35	0.06	0.40	0.08	0.80	0.16	0.70	0.07	0.90	0.05	0.50	0.05	0.502
Helios® system	0.60	0.10	0.40	0.07	0.00	0.00	0.70	0.14	0.85	0.09	0.90	0.05	0.50	0.05	0.494
SR100	0.30	0.05	0.00	0.00	0.20	0.04	1.00	0.20	0.85	0.09	0.80	0.04	0.70	0.07	0.486
PVC Portable	1.00	0.17	0.00	0.00	0.80	0.16	0.00	0.00	0.50	0.05	0.10	0.01	0.80	0.08	0.465
Standard	0.65	0.11	0.00	0.00	0.90	0.18	0.00	0.00	0.65	0.07	0.60	0.03	0.75	0.08	0.461
Biteco	0.60	0.10	0.00	0.00	0.10	0.02	0.70	0.14	0.80	0.08	1.00	0.05	0.40	0.04	0.432
Bioconstruct	0.60	0.10	0.00	0.00	0.00	0.00	0.70	0.14	0.85	0.09	1.00	0.05	0.40	0.04	0.417
Weltec	0.30	0.05	0.20	0.04	0.00	0.00	0.70	0.14	0.90	0.09	0.90	0.05	0.40	0.04	0.402
Ökobit	0.55	0.09	0.00	0.00	0.00	0.00	0.65	0.13	0.85	0.09	0.90	0.05	0.40	0.04	0.394
Floating digester	0.80	0.14	0.00	0.00	0.50	0.10	0.00	0.00	0.50	0.05	0.10	0.01	0.70	0.07	0.361

A: Cost, B: Local Availability, C: Scalability, D: OFMSW Suitability, E: Temperature Regulation Ability, F: Presence of Agitation Accessory, G: Ease of Construction, Operation and maintenance, S: Score, WS: Weighted score

The Agama Pro digester is readily available locally for small scale applications in the form of prefabricated Polyfibre tanks making it the easiest to set up since it is already finished from the supplier. The Agama digester however comes in standard non-flexible sizes with the largest capacity of 6 m^3 making it not as easy to size as well as maintain since its interior is inaccessible just like the Geo membrane digesters. No effort whatsoever was made by the technology designer to incorporate automated substrate agitation.

Generally, foreign manufactures mostly venture into large scale projects, especially the ones from Europe. However, China and India have potential suppliers that could fit into the needs of small scale biogas projects but the costs of mobilisation including import duty make imported technology uneconomical to source thereby favouring the locally available technologies.

The least preferred option of biogas plant is the floating digester produced by China's Sunrise Econergy Company Shenzhen. The digester, although an easy one to construct and quite affordable, it is not an available product on the market locally, it is not suitable for the treatment of OFMSW, only available for small scales and lacks design modifications to cater for substrate agitation and system temperature regulation as well.

Overall, the most preferred biogas digester model for the project was the Puxin digester originally from China but locally produced by BiogasSA. The plant is constructed below ground using in-situ reinforced concrete to maintain a warm temperature within the plant for optimum performance. It also runs as a hydraulic system to automatically agitate the substrate. This was closely followed by the Agama Pro digester and the Biotech's Geo membrane digester from India in that order.

5.2.2 Site Selection

5.2.2.1 Potential Alternatives

A suitable site was selected from lists of potential alternatives for setting up the AD system as showed in the subsequent sections using the WFR approach for scoring and AHP MCDA technique for prioritising the criteria and alternatives. The developed list of potential sites alongside a summary of their attributes is presented in Table 12.

Table 12: A list of alternative sites for siting the biogas digester

	A	B	C	D	E
Transfer Station (WTS)	720	50	80	Near parking area and main road	An open green site on natural ground with slight slope
Student Centre (SC)	300	700	30	Near eatery	An open green site on natural ground on flat terrain
Aurum Residence (AR)	450	250	10	Near residence	A paved flat site covered by trees

A: Area (m^2), B: Distance from waste transfer station (m) C: Distance from proposed point of use (m), D: Land Use Pattern E: Other notable physical features

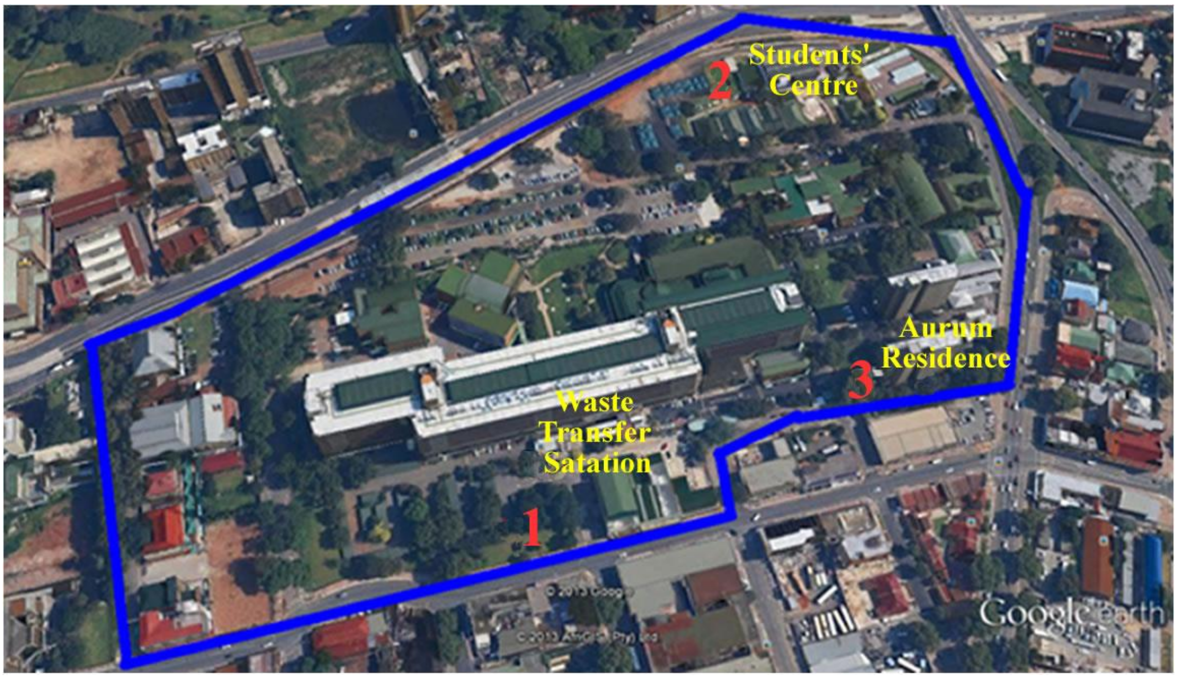

Figure 14: A google maps' satellite image of the UJ DFC showing the proposed sites

5.2.2.2 Selection Criteria

Table 13 on the other hand lists the various criteria considered for site selection and Table 14 shows their priority values obtained from the pairwise comparisons against each other using Saaty's scale of 1-9.

Table 13: Selection criteria for evaluation of the alternative sites

	Justification
A	The current land use pattern dictates the suitability of a particular site for establishment of a biogas plant. For example a proposed site located in an industrial area would be a better option than a gazetted residential area. In addition, if the proposed site is expected to be used in a way that cannot co-exist with the project in plan it makes it a project limiting factor and the project cannot go on hence given high level of importance and top priority[61, 85, 94].
B	The proposed site should have adequate space to accommodate the envisaged size of plant. The available area should also give enough working space and leave room for future expansion. Available area is a limiting factor to the project because without adequate space the project cannot proceed therefore area is given high priority [94].
C	Just like any other plant, the proposed site for the new establishment should be free of existing underground service lines such as water lines, and underground sewers among others. Presence of these would increase the project cost in relocation of the services or sometimes the project is blocked especially if the construction involves deep excavations like in the case of biogas plant installations. Therefore the high level importance[95].
D	The supply of the gas produced by the plant should have a remarkable impact on the intended point of use so as to achieve the project’s objectives. This impact is a function of the current energy demand and intended use at the point of application. Energy recovery from biogas for cooking and heating gives a higher benefit than if used for electricity. On the other hand, the place with the higher energy demand needs the extra supply more therefore the better target. Since this factor has direct bearing on the project returns, it is given high priority to ensure economic viability of the successful choice [62, 65].
E	The intended substrate or feedstock intended for use in the digester should be generated as close as possible to the site to minimise the cost of feedstock transportation. Ideally, the biogas plant should be set up in the same vicinity as the feedstock source such as a landfill in case of municipal solid waste or a cattle farm for manure. A long distance increases project costs and therefore a direct negative impact on the economic feasibility hence should be given high priority[96]
F	A proposed site for a biogas plant should have a clear ownership history void of ownership conflicts. Therefore prior to project implementation, all legal checks and ownership paperwork should be made to ensure a streamlined process of project implementation. Ownership can sometimes create major hurdles for project progress and hence given relatively middle level priority[61].
G	The digestate from the anaerobic digestion of biomass is a potent source of organic agricultural fertilizer. This should therefore be discarded in an environmentally friendly manner or applied for use within acceptable distances to reduce transportation costs. The ideal and most economical sites should be located near farm land where the fertilizer can be applied or better if it’s an area with ready market for the fertilizer. In an urban setting, the effluent can be redirected into a nearby sewer line. The site closest to a sewer line is the most preferred choice. This has some bearing on project cost and environmental impact hence gets a middle level importance[64, 65].
H	Preliminary geotechnical investigations can guide the designer on the nature of the subsoil. In cases where the hard pan is a frequent occurrence, the design installation plan must be done in such a way that deep excavations are avoided because this would then increase the construction costs tremendously. Therefore sites with evidently soft grounds are preferred to ones with paved surfaces or hard rock. However, this can be solved by advanced excavation equipment at a raised cost hence not a limiting factor and therefore given middle level importance [96]
I	The proposed site should be accessible to allow for easy access for delivery of feedstock and evacuation of the digestate as well as construction equipment. This can be solved by creating access roads hence given lower level importance[96]
J	Combustible gases burn better at high pressures. Biogas just like any other fluid moving over a considerable distance tends to have pressure drops. The longer the distance, the higher the pressure drop. To ensure optimum gas pressure over a long distance, hydraulic pumps have to be installed along the delivery pipe to step up the pressure. This in turn increases the overall cost of the project. Hence the most preferred choice of site should be as close to the point of use as possible to avoid such unnecessary additional costs. It is not a limiting factor to the project hence a lower level of importance [65].
K	For an industrial processing plant to become a success, it has to be set up in locations where the inhabitants will support its establishment. Or else, its establishment is hampered. However the attitude problem can be solved by community sensitisation via liaison channels. However, for this case study, the university owns all the potential sites outright. Hence the factor carries a low level of importance at 0.29[97]
L	The site choice should respond to the prevailing climatic conditions of the location. Bearing in mind that biogas plants operate optimally at temperature ranges between 30°C to 40°C, hence the site within the warmest location would be the most preferred alternative. But for this particular case study, the sites are affected equally by climate because they are within the same confine hence a low level of importance [98]

A: Current and future expected land use, B: Available area, C: Presence of utility lines, D: Biogas application and energy saving impact, E: Proximity to substrate source, F: Property rights, G: Proximity to digestate disposal point, H: Ground conditions, I: Accessibility, J: Distance from point of application, K: Community attitudes, L: Climatic conditions

Table 14: Priority of criteria relative to each other

Criteria	Intensity of Importance												Priority
	A	B	C	D	E	F	G	H	I	J	K	L	
A	1.00	1.10	1.10	1.30	1.50	2.00	3.00	3.00	4.00	4.00	5.00	5.00	0.157
B	0.91	1.00	1.20	1.30	1.50	1.50	2.00	3.00	4.00	4.00	5.00	5.00	0.147
C	0.91	0.83	1.00	1.20	1.30	1.50	2.00	3.00	3.00	4.00	4.00	5.00	0.134
D	0.77	0.77	0.83	1.00	1.10	1.30	2.00	2.00	3.00	3.00	4.00	5.00	0.117
E	0.67	0.67	0.77	0.91	1.00	1.20	1.80	2.00	2.00	3.00	4.00	5.00	0.106
F	0.50	0.67	0.67	0.77	0.83	1.00	1.20	1.50	2.00	2.00	3.00	4.00	0.086
G	0.33	0.50	0.50	0.50	0.56	0.83	1.00	1.20	1.50	2.00	2.00	3.00	0.065
H	0.33	0.33	0.33	0.50	0.50	0.67	0.83	1.00	1.20	1.50	2.00	2.00	0.053
I	0.25	0.25	0.33	0.33	0.50	0.50	0.67	0.83	1.00	1.20	1.50	2.00	0.043
J	0.25	0.25	0.25	0.33	0.33	0.50	0.50	0.67	0.83	1.00	1.20	1.50	0.037
K	0.20	0.20	0.25	0.25	0.25	0.33	0.50	0.50	0.67	0.83	1.00	1.00	0.029
L	0.20	0.20	0.20	0.20	0.20	0.33	0.50	0.50	0.50	0.67	1.00	1.00	0.027

A: Current and future expected land use, B: Available area, C: Presence of utility lines, D: Biogas application and energy saving impact, E: Proximity to substrate source, F: Property rights, G: Proximity to digestate disposal point, H: Ground conditions, I: Accessibility, J: Distance from point of application, K: Community attitudes, L: Climatic conditions

The current and future expected land use at the proposed site was found to be the ruling factor in making the decision of a suitable site with a priority score of 0.164 followed closely by the available area at 0.154 and the existence of utility lines as well as energy saving impact of the site at 0.134 and 0.117, respectively. The climatic pattern of the sites was the least important factor because the sites are located within the same area and therefore experiencing similar climates.

The same applies to the community attitudes, since all sites are within the same community that supports the project concepts and everything else the project stands for. Therefore, the factor is the second least important for selection. Furthermore, using the 1-9 scale, priority scores of potential alternatives were computed basing on their relative abilities to fulfil the set criteria and results from these comparisons are as showed in Table 15.

Table 15: Relative priorities of the alternative sites basing on the selection criteria

Criteria	Alternative	Intensity of Importance			Priority
		WTS	AR	SC	
Land use pattern	WTS	1.00	0.20	2.00	0.168
	AR	5.00	1.00	7.00	0.738
	SC	0.50	0.14	1.00	0.094
Area	WTS	1.00	1.30	3.00	0.480
	AR	0.77	1.00	2.00	0.352
	SC	0.33	0.50	1.00	0.168
Biogas Application and Energy Saving Impact	WTS	1.00	0.14	0.20	0.074
	AR	7.00	1.00	3.00	0.643
	SC	5.00	0.33	1.00	0.283
Proximity to substrate source	WTS	1.00	3.00	7.00	0.669
	AR	0.33	1.00	3.00	0.243
	SC	0.14	0.33	1.00	0.088
Existing utility lines	WTS	1.00	4.00	1.60	0.516
	AR	0.25	1.00	0.50	0.140
	SC	0.63	3.00	1.00	0.344
Property rights	WTS	1.00	1.00	1.00	0.333
	AR	1.00	1.00	1.00	0.333
	SC	1.00	1.00	1.00	0.333
Community attitudes	WTS	1.00	1.00	1.00	0.333
	AR	1.00	1.00	1.00	0.333
	SC	1.00	1.00	1.00	0.333
Climatic Patterns	WTS	1.00	1.00	1.00	0.333
	AR	1.00	1.00	1.00	0.333
	SC	1.00	1.00	1.00	0.333
Proximity to digestate disposal points	WTS	1.00	1.00	5.00	0.414
	AR	1.00	1.00	5.00	0.414
	SC	0.20	1.00	1.00	0.172
Ground conditions	WTS	1.00	2.00	1.00	0.400
	AR	0.50	1.00	0.50	0.200
	SC	1.00	2.00	1.00	0.400
Accessibility	WTS	1.00	0.67	0.50	0.221
	AR	1.50	1.00	0.67	0.319
	SC	2.00	1.50	1.00	0.460
Proximity to point of application	WTS	1.00	0.20	0.20	0.095
	AR	5.00	1.00	1.10	0.490
	SC	5.00	0.67	1.00	0.415

5.2.2.3 Scores and Ranking

Table 16 represents the summary of the results from the scoring and ranking of the potential sites against the prioritised selection criteria from the earlier mentioned AHP pairwise comparisons of both the alternatives against criteria and criteria against each other.

Table 16: Scores and ranks for the alternative Sites

FACTOR	Priority	SCORES WTS	SC	AR	WEIGHTED SCORES WTS	SC	AR
Current and future land use pattern	0.157	0.168	0.094	0.738	0.03	0.01	0.12
Available area	0.147	0.480	0.168	0.352	0.07	0.02	0.05
Existing utility lines	0.134	0.516	0.344	0.140	0.07	0.05	0.02
Biogas application and impact	0.117	0.074	0.283	0.643	0.01	0.03	0.08
Proximity to substrate source	0.106	0.669	0.088	0.243	0.07	0.01	0.03
Property rights	0.086	0.333	0.333	0.333	0.03	0.03	0.03
Proximity to digestate Disposal point	0.065	0.414	0.172	0.414	0.03	0.01	0.03
Ground conditions	0.053	0.400	0.400	0.200	0.02	0.02	0.01
Accessibility of site	0.043	0.221	0.460	0.319	0.01	0.02	0.01
Proximity to point of service	0.037	0.095	0.415	0.490	0.00	0.02	0.02
Community attitudes	0.029	0.333	0.333	0.333	0.01	0.01	0.01
Prevailing climatic patterns	0.027	0.333	0.333	0.333	0.01	0.01	0.01
SUM	1.000				0.36	0.24	0.40

WTS: Waste transfer station, SC: Students' centre, AR: Aurum residence

After obtaining the aggregate scores of the alternatives based on their relative scores per factor vis-a-vis the relative importance of the individual factors, the site near the Aurum residence turned out to be the highest ranked amassing a total score of 0.40 followed by the WTS and SC sites scoring 0.36 and 0.24 respectively. Hence the most suitable site for the proposed biogas plant is the AR site followed by the one near the current waste transfer station (WTS) and lastly the one near the students' centre (SC). The most preferred site was the one near the Aurum ladies' residence at which the gas will be used to for heating purposes.

The site near the transfer station does not conflict much with existing land use patterns since it is secluded surrounded by car parks and the school boundary hedge line with the main road hence making it a good potential site. On the other hand, the site near the student centre is so close to an eating place and could become a problem as biogas production from waste is most often associated with foul odours and the one near the residence is situated near a residence though quite secluded from the habitable sections of the building.

In addition, after further consultation with the estates department of the school, it was revealed that the two sites that is the SC and WTS had been earlier on earmarked as future parking spaces reducing their relevance to meeting the project's objectives and hence the low priority scores of 0.094 and 0.168, respectively, leaving the AR site with the highest score of 0.738 with respect to current and expected land use pattern as a selection criterion.

The site near the WTS has a large available area which is bigger than the other 2 sites. Hence, the WTS site ranks highest with regards to area as a measurement factor with a score of 0.480. The AR and SC sites scored 0.352 and 0.168, respectively.

The biogas generated at the site near the Aurum residence is meant for heating at the residence which has been an ongoing concern especially during the cold winters. And, the biogas that would be generated near the students' centre is proposed to be used for cooking at one of the canteens where they are currently relying on electricity and natural gas. Near the waste transfer station, the closest point of use for the generated gas are the laboratories in the neighbourhood whose gas demand is not so high, but would find occasional application on Bunsen burners. Comparing all the three applications, the use of the biogas at the Aurum residence gives the highest energy yield followed by cooking at the students' centre and finally the laboratories near the waste transfer station hence the scores of 0.643, 0.283 and 0.074 for the AR, SC and WTS, respectively with respect to biogas application and energy saving impact as a selection criterion.

Evidently, the site near the waste transfer station is the closest to the feedstock source which is the waste transfer station, ranking highest compared to the rest with respect to proximity to substrate source scoring 0.669 followed by the site near the Aurum girls' residence at 0.243 and the farthest and least ranked is the students' centre site at 0.88.

On the basis of visual inspection and preliminary surveys, combined with stakeholder consultation, the probabilities of each of the sites having underlying service lines within the envisaged space were obtained and used as the respective scores with respect to presence of below-ground utility lines as a selection factor. The higher the probability, the lower the priority score and vice versa. The AR site had the highest probability hence a low priority score of 0.140 and 0.516 and 0.344 for the WTS and SC sites, respectively.

All three sites are located within the same vicinity under 1000 m radius and are owned by the University of Johannesburg whose drive towards process energy and environmental engineering research supports the establishment of the biogas plant. This implies that all these sites experience similar climate and therefore all score equally. The ownership details of all the sites are clear, all belonging to the university. In addition, all proposed sites are within a community that will embrace the envisaged technology and therefore all score equally with regards to community attitudes as a selection factor.

There are existing sewer lines not so far away from the WTS and AR sites to which the digestate could be directed after the digestion processes hence both sites scoring equally at 0.414. The SC site is relatively farther from possible disposal points for the generated digestate. This gives the SC site the lowest score at 0.172.

The SC and WTS sites are both fresh green sites covered by grass on natural soft ground making them rather easy for plant establishment especially where deep excavations will be involved. Hence, the two sites score equally at 0.414 with regard to ground conditions. In contrast, the site behind Aurum residence is partly paved in some areas with an asphalt concrete surface making any envisaged excavations for civil works harder hence scoring lowest at 0.172.

The site near the students' centre has clearer access routes that don't require further modification, and therefore, scores highest at 0.46. However, the TS and AR sites both have constraints to a certain degree as regards accessibility with the AU site having easier access scoring 0.319 and lastly the TS site with 0.221.

The biogas from the site near the waste transfer station is proposed to be used in the nearby laboratories that are quite far from the site making it the least ranked site scoring 0.095. The other two sites are relatively close to their intended points of use hence almost at equal ranking but the one at Aurum ladies' residence is much closer and therefore most highly ranked at 0.49.

5.3 System Components and Dimensioning

For the proposed system, the design would include a food waste macerator with a hopper for substrate homogenisation and particle size reduction, a holding or mixing tank for temporary storage of the substrate prior to feeding into the Puxin digesters which will digest the feedstock anaerobically and produce biogas delivered through rubber delivery pipes into the building's LPG powered heating system. The delivery pipes will be equipped with desulphurisers to reduce the H_2S content in the biogas. The produced digestate will be fed into a nearby sewer line. A schematic of the proposed system is showed in Figure 15.

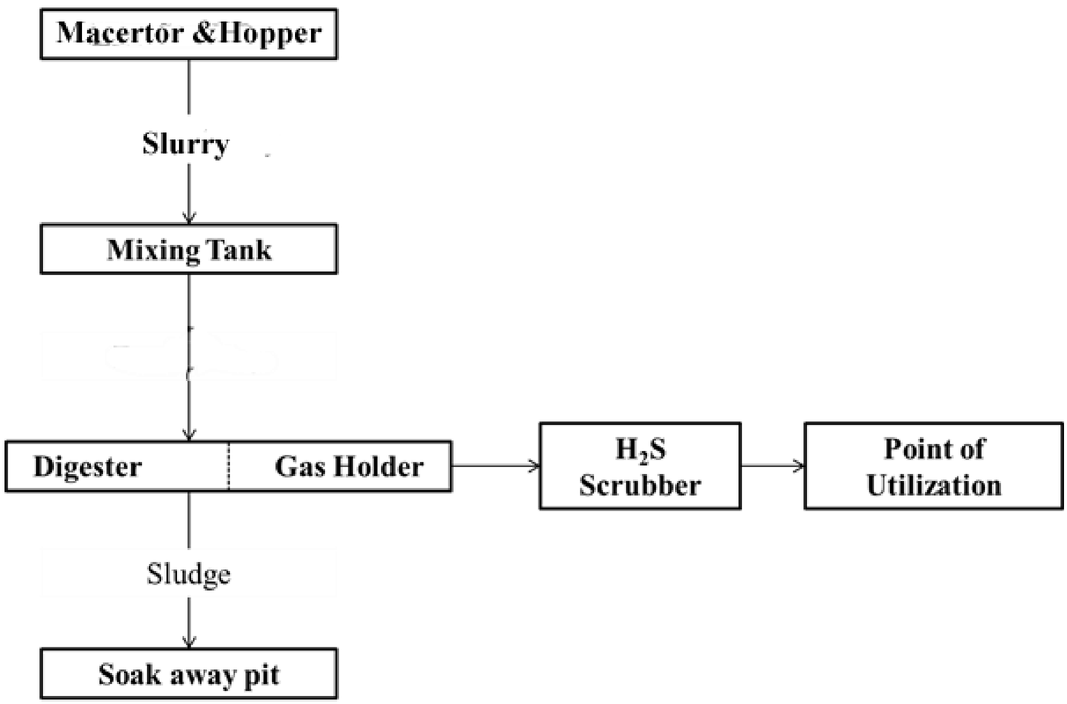

Figure 15: System general layout and schematic

All system components will be interconnected by a network of pipes secured with valves. Detailed drawings of the layout produced using Inventor CAD software can be found in the appendix section 8.2 of this document and the descriptions of the various components are as discussed below;

5.3.1 Macerator and Hopper Assembly

The organic waste will be collected daily using temporary storage bins from the waste transfer station which will then be transferred to the site. This will be fed into a hopper assembly mounted onto a 2.24 kW macerator to reduce the feedstock particle sizes to at least 5mm. This assembly will be feeding into a mixing tank and the shredded substrate will then be mixed with a measured amount of water to form a slurry that makes microbial activity easier and faster. A typical organic solid waste macerator and hopper assembly is as showed in Figure 16.

Figure 16: A typical food waste macerator with a hopper

5.3.2 Mixing tank

The system will incorporate a concrete cast mixing tank which will serve as a buffer for generated feedstock to control the rate as well as the quality of input feedstock. The tank will be set up at a 0.5m above ground to eliminate the need for pumping the slurry into the digesters. Therefore, the slurry will flow out under gravity into the digester which will be an underground installation. Figure 17 shows a typical example of a mixing tank.

Figure 17: A brickwork mixing tank

5.3.2.1 *Mixing Tank Sizing*

The capacity of the mixing tank will be equivalent to a 4 days' discharge to account for possible long weekends or system shut down. Using equation 13 and the volumetric flow rate of 0.6 m^3 from Table 7, the capacity of the tank was obtained as 2.4 m^3. Therefore the tank volume can be taken as 2.4 m^3 with dimensions of 1 m height, 2m length and 1.2m wide. The tank will utilise the existing water connections to tap water from the nearest point via hose pipes.

5.3.3 Digester

From section 5.2.1, the preferred choice of anaerobic digester model selected was the Puxin digester. This model is available in 10 m^3 units built from in-situ steel reinforced concrete with feedstock inlet and digestate outlet chambers made out of brickwork and a demountable fibreglass gas holder. Hence, the system will be comprised of three (3 No.) 10 m^3 biogas digesters setup in parallel. The whole assembly is airtight not only to prevent the escape of the biogas but also to prevent the entrance of air since the methanogens thrive well only in the absence of oxygen. The digester will be fed continuously at the prescribed daily rate of 0.6 m^3

per day from the mixing tank. The construction will be below ground, hence temperatures will be maintained within the required values and agitation of substrate is by hydraulic action though occasional manual agitation will seldom be required. Details of the digester design drawings are as showed in the appendix section 8.2.

5.3.4 Piping

The piping system will be comprised of two parts; a network of 6 inch diameter PVC pipes inter-connecting the digester inlets to the mixing tank as well as the outlets to the existing nearby sewer line and 1 inch diameter flexible rubber delivery pipes for distributing the biogas to the points of application. The distribution network of the 1 inch rubber pipes will be safely secured by valves to prevent gas leakage both at gas holder and at points of application as well as to control substrate discharge.

5.3.5 Pressure gauges

A 16 kPa pressure gauge will be installed on the gas line as a safety measure to monitor the pressure in the gas holder. The gas pressure gauge can also work as a monitoring system for pipe blockages. In the event that a blockage occurs anywhere in the gas line, the gauge downstream will record a lower pressure reading than that upstream.

5.3.6 Hydrogen Sulphide (H_2S) Scrubber

H_2S as one of the trace compounds from biogas production is very poisonous, corrosive and may even cause the embrittlement of metal. Hence, it is essential that it be removed from the biogas before using it as a fuel. A practical way to remove the H_2S is by passing the biogas through a desulphuriser. This could be layers of iron fillings or activated carbon in a closed container. The desulphuriser to be used will be a plastic PX-1L type supplied by Shenzen Puxin technology company limited, China which can treat up to 5 m^3 of biogas per day and should be replaced after treating 200 m^3. A typical Puxin desulphuriser is as in Figure 18.

Figure 18: A Puxin desulphuriser

5.4 Energy Usage Assessment

This section shows the comparative analysis of the energy consumption against the energy produced from the proposed AD system. The values used are obtained from research and reference to product manufacturers' catalogues.

From section 4.3, the estimated daily generation rate for the biogas was 23.014 m^3 per day at 62% methane content. Taking the energy content of 10 kWh per Nm^3 of pure methane [99], the energy production per day from the system will be 142.7 kWh per day hence 52, 085 kWh annually. On the other hand, from section 5.3, the system will be equipped with a 2.24 kW feedstock macerator assembly running for an estimated 1 hour per day giving an overall annual energy consumption of 818 kWh /year. The system will not have external heating and substrate agitation will be carried out automatically and manually. Water to be used on the system will be piped from existing nearby lines and the digestate will flow by gravity into an existing sewer line hence no pumps required. Table 17 shows the summary of the energy balance of the proposed system.

Table 17: System energy balance

Item	Energy Input (kWh)	Energy Output (kWh)
Biogas production		52, 085
Grinder	818	
Total	818	52, 085
Energy surplus		**51, 267**

5.5 System Economic Analysis

New technologies cannot be presented as solutions or implemented without a proper understanding of their costs against benefits. The major point of concern is always the pay-back time as no one wishes to invest into non-profitable ventures. A cost-benefit analysis was conducted for the proposed system taking into account the initial cost of system set up, maintenance costs against savings from energy recovery and savings from reduced MSW landfilling.

From the biogas technology supplier BiogasSA based in Johannesburg, the cost of one Puxin digester was found to be at R60, 000 with an installation and system integration cost of R10, 000. In addition, the plants have a service life of 50 years which gives an annual depreciation rate of 2%. A 2.24 kW macerator was estimated at R30, 000 and the concrete mixing tank at R6, 000 [100]. From section 4.3, the feedstock will require an additional 1 kg of industrial grade sodium bicarbonate per day for purposes of pH regulation which costs R3 on the market. Currently the cost of landfilling biowaste in Johannesburg is R200 per ton and the UJ DFC is currently generating 231.22 kg of biowaste per day implying an annual collection of 84.4 tons [101]. As of October 2014, the cost of LPG gas was R22.69 per kg. At a calorific value of 12.086 kWh per kg, the cost of using LPG for heating was R1.88 per kWh hence this was adopted as the saving realised from substituting the LPG gas for biogas at the hostel for heating [102]. Table 18 shows a summary breakdown of all the expected benefits from the project against the costs and Table 19 shows a detailed cost-benefit analysis of the figures from Table 18 with net present values (NPV), internal rate of return (IRR) and cost-benefit ratio (CBR) analysed over a 20 year economic period.

Table 18: A breakdown summary of benefits and costs

Item		Unit	Quantity	Rate (R)	Amount (R)
Initial Costs	$10m^3$ concrete anaerobic Puxin digesters	No.	3	60,000	180, 000
	2.4 m^3 concrete mixing tank	No.	1	6,000	6, 000
	2.24 kW Macerator	No.	1	30,000	30, 000
	Installation cost and piping	No.	3	10, 000	30, 000
	Contingence	%	5	N/A	14, 000
Sub-total of initial costs					**260, 000**
Annual Costs	Alkali pre-treatment	kg/year	365	3	1, 095
	Depreciation	%	2	260, 000	5, 200
	Operation and Maintenance	%	10	260, 000	26, 000
Sub-total of annual costs					**32, 295**
Benefits	Anaerobic digestion of biowaste	ton	84.4	200	16, 880
	Energy Utilisation	kWh	51, 267	1.88	96, 382
Sub-total of annual benefits					**113, 262**

Generally, OFMSW to energy AD systems have higher operational costs associated with substrate pre-treatment. In this case, there was an additional cost as a result of inclusion of a macerator and alkali pre-treatment which would not be the case for most typical AD substrates such as farm manure and municipal sewerage. The cost of sorting the solid waste was avoided since the University campus already has an existing waste management system that incorporates sorting.

Table 19: Detailed cost benefit analysis

Year	Benefits (ZAR)	Costs (ZAR)	Net Benefit (ZAR)	Discounting Factor	Present Values (ZAR)	Cumulative Net Present Values (ZAR)
0	0	260000	-260000	1.000	-260000	-260000
1	113262	32295	80967	0.917	74282	-185718
2	113262	32295	80967	0.842	68148	-117570
3	113262	32295	80967	0.772	62521	-55049
4	113262	32295	80967	0.708	57359	2310
5	113262	32295	80967	0.650	52623	54933
6	113262	32295	80967	0.596	48278	103211
7	113262	32295	80967	0.547	44292	147503
8	113262	32295	80967	0.502	40635	188137
9	113262	32295	80967	0.460	37279	225417
10	113262	32295	80967	0.422	34201	259618
11	113262	32295	80967	0.388	31377	290996
12	113262	32295	80967	0.356	28787	319782
13	113262	32295	80967	0.326	26410	346192
14	113262	32295	80967	0.299	24229	370421
15	113262	32295	80967	0.275	22229	392649
16	113262	32295	80967	0.252	20393	413043
17	113262	32295	80967	0.231	18709	431752
18	113262	32295	80967	0.212	17164	448916
19	113262	32295	80967	0.194	15747	464664
20	113262	32295	80967	0.178	14447	479111

A plot was made of the cumulative net present values against time over the 20 year period to assess the point at which the project costs finally equal the benefits to give a net present value of 0. This is as showed in Figure 19. From Table 19, the project yields a positive net present value R479, 111 and a benefit-cost ratio of 1.86 in the 20 year economic period. This implies that the project is financially viable. In addition, the project yielded an internal rate of return of 31% which is higher than the existing rate in the capital markets which is at an average 9%.

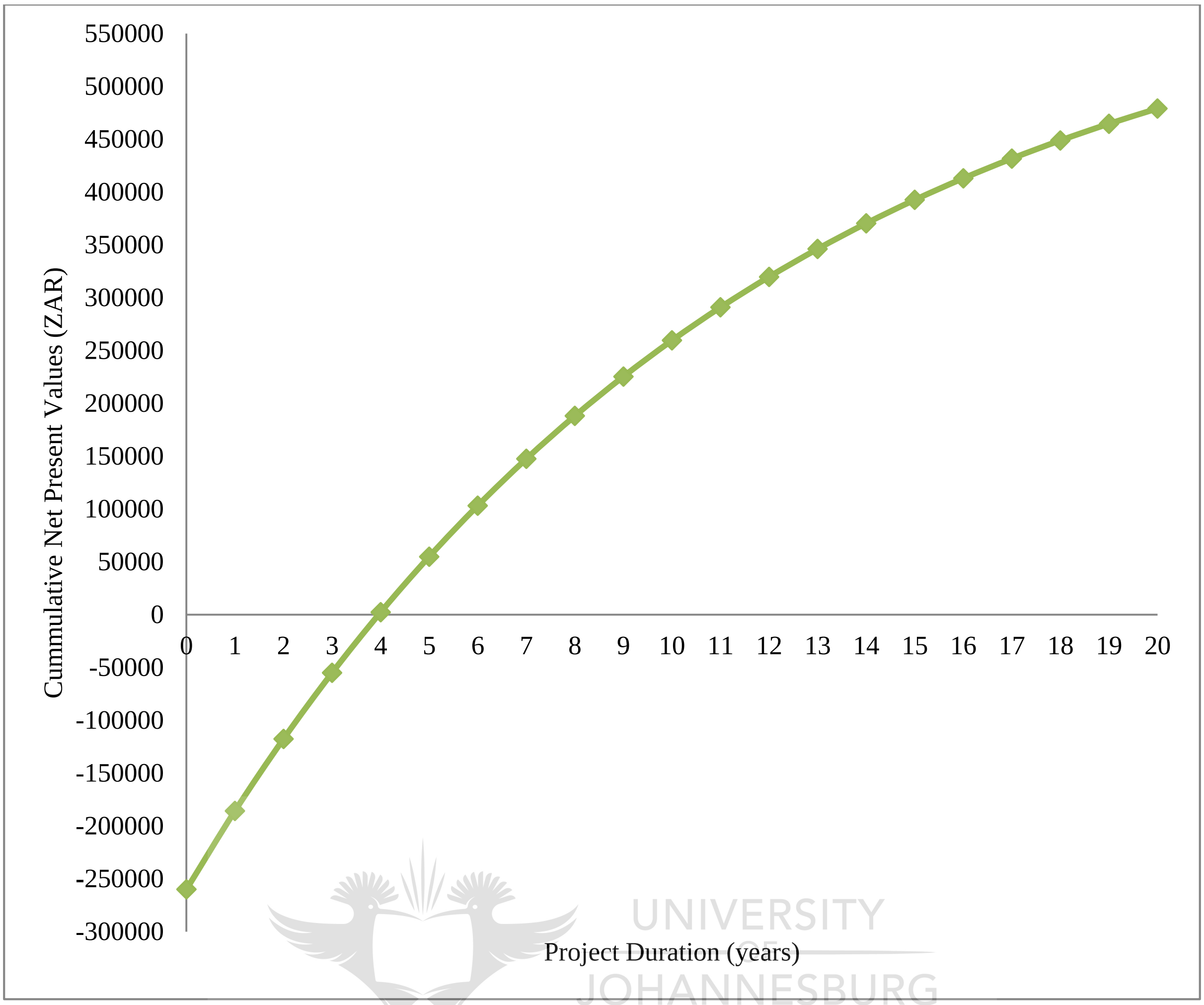

Figure 19: A plot of cumulative net present values against project duration

From Figure 19, the project is seen to breakeven within its 4th year and therefore has a payback period of 4 years. Despite the above good positive results, the overall economic viability of the project can further be improved by the introduction of other revenue streams to maximise the benefits for example by the inclusion of carbon credits as well as government subsidies.

5.6 Safety Considerations

Biogas production from biomass via AD technology is associated with several environmental, health and safety hazards. Such hazards can pose a threat to the safety of the biogas plant operators, users, visitors and the environment at large. Therefore, a careful risk assessment of the potential hazards has to be undertaken alongside the corresponding control strategies to minimise the risk of their occurrences. Such hazards include but not limited to asphyxiants, explosion potential, working in confined spaces and burns among others.

5.6.1 Hazards of an AD System

5.6.1.1 Explosion Potential

Biogas is made up of 50-70% methane, 30-50% and other trace compounds such as hydrogen sulphide. Methane when mixed with air in the right proportions is a flammable gas. Therefore, as a safety precaution, the biogas plant operator must take extra care to ensure that the methane gas that escapes does not exceed the combustible levels. Usually it is 5% and 15% by volume of air as the lower and upper limits respectively for methane.

5.6.1.2 Asphyxiants

Any gas that is capable of hindering the human cellular oxygen uptake is called an Asphyxiant. Carbon dioxide and Methane both of which are the major composition of biogas are simple asphyxiants whereas Ammonia and Hydrogen sulphides though present in trace concentration are both chemical asphyxiants. This implies that inhalation of these gasses beyond particular concentrations can be fatal. Therefore operators of AD systems should have nose masks at all times and prevent direct inhalation of biogas.

5.6.1.3 Confined Spaces

In accordance to the Occupational Safety and Health Administration (OSHA) guidelines, a confined space is that working space that has just enough area to permit bodily access but has a restricted means of entry and exit and is not set up to favour prolonged occupancy. Maintenance operations of biogas digesters usually require physically going inside to clean the reactor by manually removing the indigestible residuals at the base. The components of biogas including CO_2, CH_4 and H_2S present a high potential for asphyxiation, fire or explosion to the maintenance team. Hence the team should be given ample training on how to work in confined spaces and emphasis should be put on PPE use such as the use of safety harnesses while descending inside the reactor. The atmosphere inside the reactor should be thoroughly inspected with gas detectors to ensure that its composition is safe for human occupancy prior to entry. According to OSHA, 1998 standard, the acceptable levels for human occupancy are; O_2 level must be at least above 19.5% by volume of air, CH_4 must be below 5% by volume of air and H_2S level must be below 20 ppm.

5.6.1.4 Feedstock and Digestate Spills

Care must be taken to ensure that feed material and digestate are spilled to the environment. This can be quite harmful to the surroundings as well as the workers. However, in the event that this occurs, workers should have in place a rapid response strategy to contain the spillage. Usually the first step is to control the source of the spill and then followed by setting up temporary containment structures until a permanent solution is devised.

5.6.1.5 Drowning

Biogas digesters are fluid containment tanks and therefore pose a drowning threat. For that matter rescue equipment such as ring buoys and ropes should be made readily available on site.

5.6.2 Controls

With adequate precautionary measures, an AD facility can be a safe working environment. This section highlights some of the measures that can be put in place so as to maintain a safe working environment.

5.6.2.1 Preparation of a Clear Emergency Action Plan (EAP)

The facility prior to commissioning, a proper EAP should be put in place assessing all the probable risks alongside the controls. The EAP should give in precise detail response protocols to specific emergencies. In addition the plan should highlight key contact people, directions to the plant and site plan as references in case of an emergency.

5.6.2.2 PPE and Emergency Equipment

Personnel protective equipment should be availed and used at all times in the vicinity of the plant. This applies to both the workers and site visitors. Among the must have equipment are; Gloves, Ring buoy, Safety glasses, Safety harnesses, safety boots and coveralls. In addition the facility should have ready to use compliant emergency response equipment such as; First aid kits, Fire extinguishers, rigging equipment for rescue operations, Multi-gas detectors with extension hose and shovels.

5.6.2.3 The use of permit to work (PTW) systems

Prior to any major operations, inspections must be carried out to ensure that everything is done in accordance to the standard occupational healthy safety and environmental (HSE) procedures. The inspections and subsequent approvals have to be carried out by a competent HSE practitioner. Therefore a precise document has to be prepared detailing the tasks involved in an operation accompanied with the probable hazards alongside the controls to be put in place.

5.6.2.4 Caution Signs

Reflective boards and cards with visible warning inscriptions should be installed all around the site wherever there is a slight probability of a hazard. These should promptly be covered or even removed in case the hazard ceases to exist. Such signs for a biogas site can bear statements like; flammable gas, drowning hazard and a reminder that PPE must be worn at all times while at the plant among others. In addition to visibility, the signs should be written in languages that are understood by the likely users or visitors of the plant for example, for the UJ SANEDI project, the signs will be in English, Afrikaans and IsiZulu.

5.6.2.5 Personnel Safety Training

The operators and users of the plant should be given periodic safety training on the safe running of the plant. This can be done annually. Newly recruited plant employees should not be permitted to work on the plant until they have completed the required safety training. The plant's emergency action plan should annually be reviewed and revisions made whenever and wherever necessary.

CHAPTER 6: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusions

The anaerobic digestion of the organic fraction of municipal solid waste is a practical and environmentally sustainable solution to integrated solid waste management. It simultaneously offers a potential solution to the growing challenges of energy insecurity and environmental degradation from greenhouse gas emissions as a result of solid waste landfilling and the over-dependence on fossil fuels.

In this study, an anaerobic biodigestion system was designed for the University of Johannesburg's Doornfontein Campus (UJ DFC) in the built-up downtown Johannesburg, South Africa to treat the OFMSW generated at the campus and produce biogas to be utilised locally. The UJ DFC produced 378 kg of municipal solid waste per day of which 231.22 kg was the organic fraction composed of food waste and garden waste. The feedstock had an in-situ density of 775 kg/m^3 with a total solids (TS) content of 27.14%, volatile solids (VS) content of 94.9% and C/N ratio was 1:25. BMP tests showed that the feedstock had a biogas generation potential of 386.46 ml/g VS at an average composition of 62% methane content.

This waste required a biogas digester of 30 m^3 capacity to be efficiently treated. Fourteen (14) digester models were evaluated for selection and the Puxin digester was the most preferred. This model is available in 10 m^3 units as the largest size implying that the system would require three plants to satisfy the design capacity. On the hand, preliminary site selection yielded three (3) potential alternatives of which the site close to the Aurum ladies' residence turned out to be the most preferred at which the produced gas would be used for heating purposes to replace liquefied petroleum gas (LPG).

Generally, food waste to energy AD systems have higher operational costs associated with substrate pre-treatment. In this case, there was an additional cost of including a macerator and alkali pre-treatment which would not be the case for most typical AD substrates such as farm manure and municipal sewerage. An energy evaluation of the system showed that it had a potential to produce a surplus of 51.3 MWh of energy annually and economic analyses over a 20 year economic period revealed that the system was economically viable with a breakeven period of 4 years, BCR of 1.86, IRR of 31% and a positive NPV of R479, 111.

6.2 Recommendations and Future Work

Despite the good positive results from the economic analyses, the overall economic viability of the project could further be improved by the introduction of other revenue streams to maximise the benefits for example the inclusion of carbon credits as well as government subsidies. Therefore, municipal governments should encourage AD of OFMSW through provision of subsidies to potential investors as well as provision of interest-free loans.

In addition, it should be noted that the values obtained from the BMP tests were based on a laboratory-scale setup in a controlled environment assuming perfectly mesophilic conditions. Previous studies have showed that biomethane potential values can drop to as low as 20-40% in cold seasons (winter) as opposed to optimum performance in the warm seasons (summer) [103, 104]. Therefore, since the study area experiences all four seasons annually, further studies can be carried out at pilot scale to determine accurately the effect of seasonal variation to digester temperatures, OLR, HRT as well as biomethane potential.

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APPENDICES

RESEARCH OUTPUTS

Journal paper

- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Technology selection and siting of a biogas plant for OFMSW via multi-criteria decision analysis.* **The South African Journal of Chemical Engineering** (Accepted October 2014).

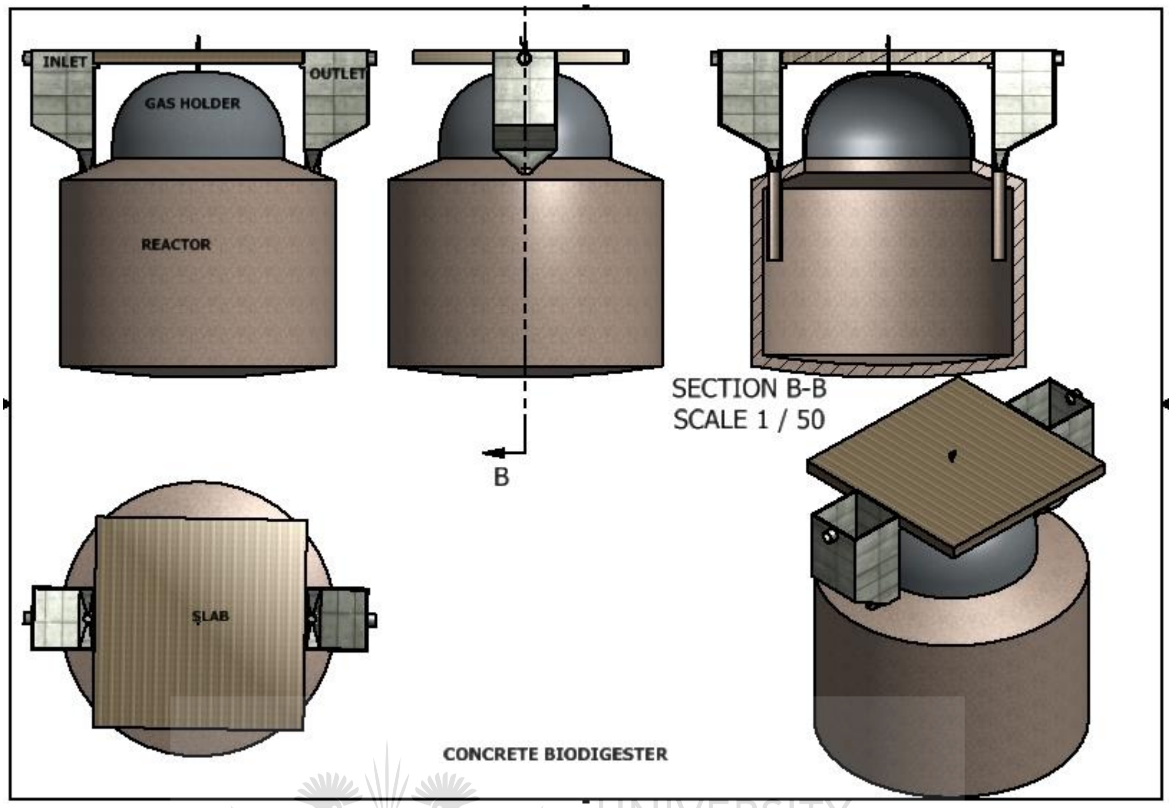
Conference papers

- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Bio-methane Potential of the Organic Fraction of Municipal Solid Waste",* **the 6th International Conference on Green Technology, Renewable Energy and Environmental Engineering (ICGTREEE '2014),** Cape Town, South Africa November 2014
- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Biogas Technology: Current Trends, Opportunities and Challenges,* **the 6th International Conference on Green Technology, Renewable Energy and Environmental Engineering (ICGTREEE '2014),** Cape Town, South Africa November 2014.
- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Sizing of an Anaerobic Biodigester for the Organic Fraction of Municipal Solid Waste,* **World Congress on Engineering and Computer Science, (WCE' 2014),** San Francisco California, United States of America. October 2014.

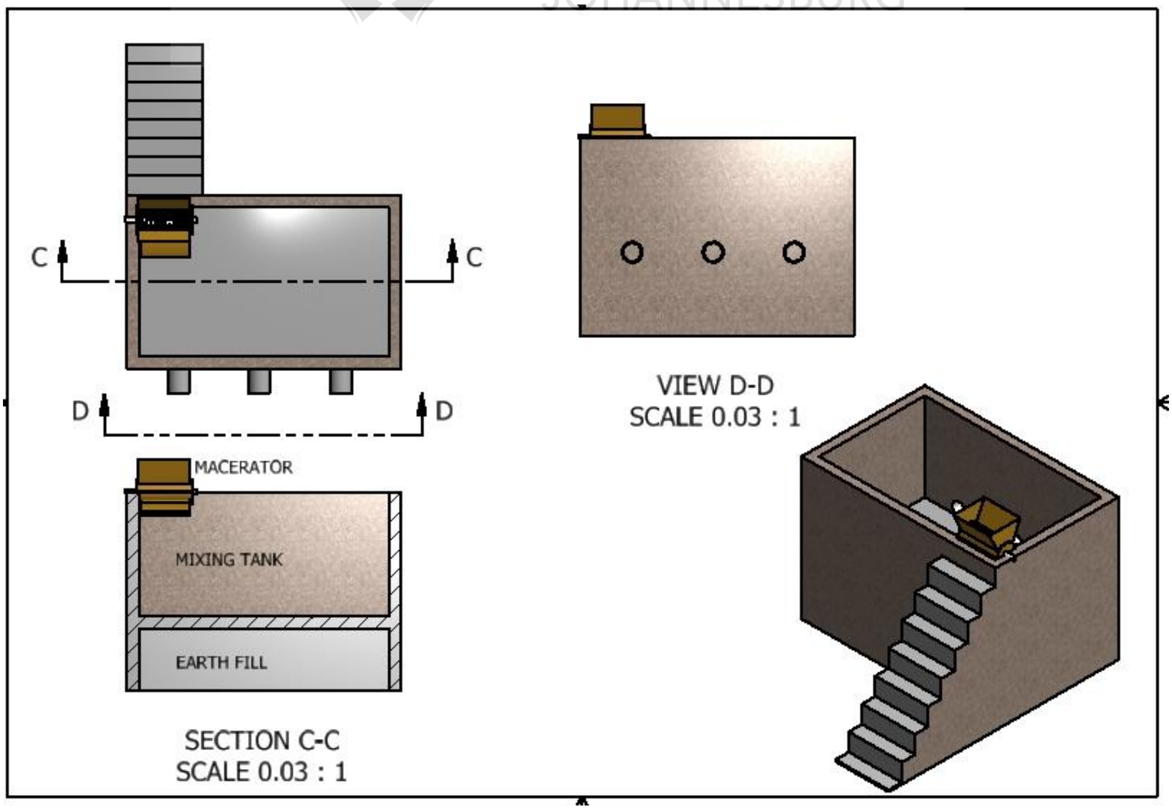
- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Technology Selection of Biogas Digesters for OFMSW via Multi-criteria Decision Analysis,* **World Congress on Engineering and Computer Science, (WCE' 2014),** London, United Kingdom. July 2014.

- Robert Kigozi, Akinwale Aboyade and Edison Muzenda, *Biogas production using the organic fraction of municipal solid waste as feedstock,* **The International Conference on Advances in Engineering Sciences and Applied Mathematics (ICAESAM' 2013),** Capet Town, South Africa December 2013.

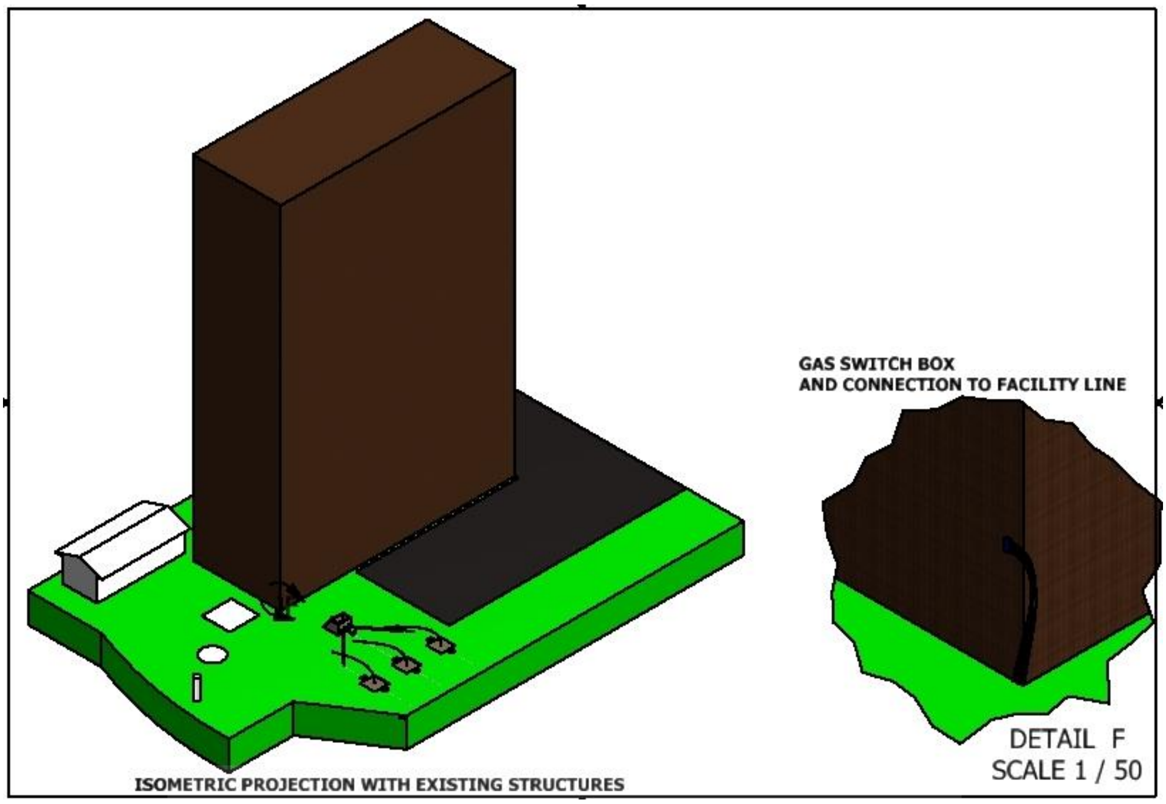
DETAILED DRAWINGS OF SYSTEM COMPONENTS AND LAYOUT



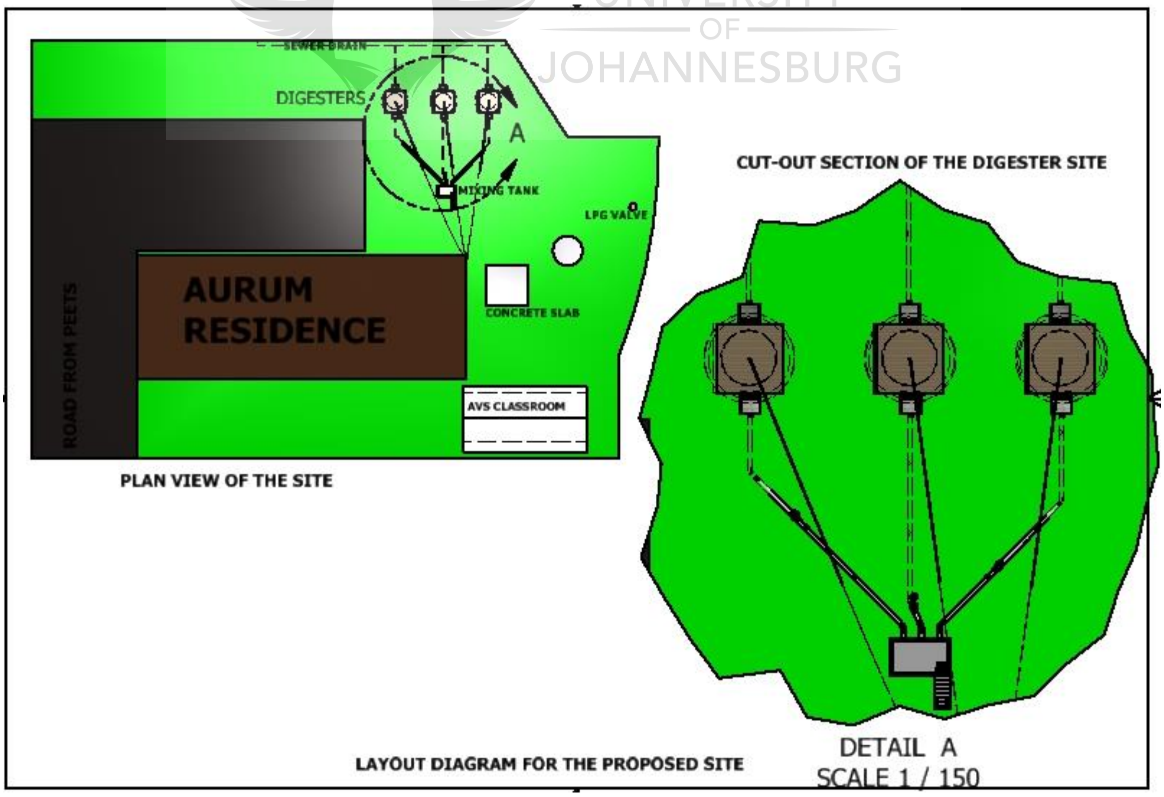
CAD representaion of the Puxin digester



Macerator and hopper assembly



A three dimesional view of the proposed site



Plan view of the proposed site and connection detail

RAW DATA

Daily generation of the general waste per category over the spring and autumn seasons in kg

GENERAL WASTE

SPRING SEASON

DATE	CATEGORY					
	Recyclables	**Paper bags**	**Food**	**Polystyrene**	**Uncategorised**	**TOTAL**
16-Sep-13	43.15	6.80	136.10	4.70	31.00	221.750
19-Sep-13	38.57	36.70	140.70	4.10	37.80	257.870
23-Sep-13	46.98	5.10	137.17	3.60	32.90	225.750
26-Sep-13	37.97	4.85	160.20	3.63	33.20	239.850
30-Sep-13	49.27	3.88	142.68	3.20	40.80	239.830
03-Oct-13	48.48	3.37	168.22	4.00	28.70	252.770
07-Oct-13	46.00	22.80	139.40	4.20	29.00	241.400
10-Oct-13	36.70	46.70	110.70	2.10	35.67	231.870
14-Sep-13	43.75	51.90	103.60	2.40	42.05	243.700
17-Sep-13	52.05	40.50	106.10	4.35	46.70	249.700

AUTUMN SEASON

DATE	CATEGORY					
	Recyclables	**Paper bags**	**Food**	**Polystyrene**	**Uncategorised**	**TOTAL**
17-Mar-14	60.45	1.51	81.63	12.77	61.60	217.955
28-Mar-14	169.91	4.28	108.85	9.08	52.49	344.615
31-Mar-14	78.90	3.89	106.38	5.36	65.83	250.361
04-Apr-14	39.50	2.70	114.56	4.18	50.21	211.151
07-Apr-14	92.80	2.90	67.51	5.70	68.00	236.912
11-Apr-14	87.90	2.89	76.38	7.36	95.83	270.361
14-Apr-14	94.75	3.28	98.85	6.08	60.49	245.452
18-Apr-14	34.16	3.05	110.65	3.80	25.67	177.326

Daily generation of the garden waste per category over the spring and autumn seasons in kg

GARDEN WASTE			
SPRING SEASON			
DATE	**CATEGORY**		
	Compostable	**None Compostable**	**TOTAL**
17-Sep-13	79.36	10.63	89.99
24-Sep-13	106.13	5.79	111.92
01-Oct-13	117.71	7.23	124.93
08-Oct-13	89.54	6.96	96.50
15-Oct-13	101.26	8.41	109.67
AUTUMN SEASON			
DATE	**CATEGORY**		
	Compostable	**None Compostable**	**TOTAL**
18-Mar-14	121.05	40.85	161.900
26-Mar-14	94.64	16.70	111.331
04-Apr-14	152.01	21.78	173.790
09-Apr-14	184.12	35.17	219.292
17-Apr-14	115.99	24.88	140.866

Feedstock in situ density

Parameter	Sample				Average
	1	2	3	4	
Mass of container (kg)	0.118	0.117	0.12	0.115	0.1175
Mass of Sample + Container (kg)	0.321	0.314	0.298	0.312	0.31125
Mass Sample (kg)	0.203	0.197	0.178	0.197	0.19375
Volume of container (m^3)	0.00025	0.00025	0.00025	0.00025	0.00025
Density (kg/m^3)	812	788	712	788	775

Feedstock total solids and moisture content

	Aliquot				Average
Parameter	1	2	3	4	
Mass of Dish and Watch glass (md) (g)	95.67	90.46	95.65	95.55	94.33
Mass of Sample + Dish (ms) (g)	128.87	123.64	128.66	128.66	127.46
Mass Sample (g)	33.20	33.18	33.01	33.11	33.12
Total Mass of Dry Sample (msd) (g)	105.29	100.07	103.91	104.02	103.32
Mass Total Solids (g)	9.62	9.61	8.25	8.47	8.99
Mass Moisture (g)	23.58	23.56	24.76	24.63	24.13
% Moisture Content	71.02	71.03	75.00	74.41	72.86
%Total Solid (TS) Content	28.98	28.97	25.00	25.60	27.14

Feedstock volatile and fixed solids content

Parameter	Aliquot 1	2	3	4	Average
Mass of Dish and Watch glass (md) (g)	95.67	90.46	95.65	95.55	94.33
Total Mass of Residue of Total Solids +Dish (msd) (g)	105.29	100.07	103.91	104.02	103.32
Mass of Residue after furnace heating at 550ºC (g)	96.11	90.90	96.11	96.03	94.79
Mass volatile Solids (g)	9.18	9.17	7.79	8.00	8.53
Mass fixed solids (g)	0.44	0.44	0.46	0.48	0.46
%Fixed Solids	4.60	4.61	5.57	5.65	5.11
% Volatile solids	95.41	95.39	94.43	94.35	94.89

Feedstock elemental compositions

Parameter	**Element** **C**	**H**	**O**	**N**
Percentage Composition	52.8	6.02	38.42	2.1
Elemental Atomic Mass (g/mol)	12	1	16	14
Number of moles	4.4	6.02	2.4	0.15
Empirical molar values	29.33	40.13	16.01	1
Approximation	28	38	15	1
Feedstock Chemical formula		$C_{28}H_{38}O_{15}N$		
C:N ratio		25:01		

Daily biogas generation

Time	Cummulation Time	Setup 1	Setup 2	Setup 3	Setup 4	Average	Specific	Per Day	Rate (ml/day)
0.0	0.0	0	0	0	0	0	0.00	0.00	0.00
0.4	0.4	78	103	150	1629	490	12.68	490.00	1225.00
0.6	1.0	1800	2751	330	2472	1838	47.58	1348.25	2247.08
0.4	1.4	2780	4616	1236	3155	2947	76.27	1108.50	2771.25
0.6	2.0	4022	5480	2626	4551	4170	107.93	1223.00	2038.33
0.4	2.4	4332	5664	3294	4883	4543	117.60	373.50	933.75
0.6	3.0	5016	6499	3839	5751	5276	136.57	733.00	1221.67
0.4	3.4	5250	6967	4570	5976	5691	147.30	414.50	1036.25
0.6	4.0	5650	7290	5223	6294	6114	158.26	423.50	705.83
0.4	4.4	7385	8194	6248	7183	7253	187.72	1138.25	2845.63
0.6	5.0	8025	9088	6780	7924	7954	205.89	701.75	1169.58
0.4	5.4	8913	9980	8161	8835	8972	232.24	1018.00	2545.00
0.6	6.0	9571	10798	8590	10280	9810	253.92	837.50	1395.83
0.4	6.4	10641	11007	9783	10750	10545	272.95	735.50	1838.75
0.6	7.0	11104	11792	10599	11120	11154	288.70	608.50	1014.17
0.4	7.4	11740	12204	11108	11934	11747	304.05	592.75	1481.88
0.6	8.0	11980	12994	11592	12098	12166	314.91	419.50	699.17
0.4	8.4	12005	13481	11800	12202	12372	320.24	206.00	515.00
0.6	9.0	12095	14375	11950	12350	12693	328.53	320.50	534.17
0.4	9.4	12281	14809	12092	12403	12896	333.81	203.75	509.38
0.6	10.0	13045	14992	12586	13028	13413	347.18	516.50	860.83
0.4	10.4	14597	15280	13902	14550	14582	377.45	1169.50	2923.75
0.6	11.0	14684	15475	14306	14605	14768	382.24	185.25	308.75
0.4	11.4	14702	15502	14490	14618	14828	383.81	60.50	151.25
0.6	12.0	14798	15570	14508	14625	14875	385.03	47.25	78.75
0.4	12.4	14862	15590	14548	14627	14907	385.85	31.50	78.75
0.6	13.0	14911	15608	14551	14647	14929	386.43	22.50	37.50
0.4	13.4	14916	15618	14551	14680	14941	386.74	12.00	30.00
0.6	14.0	14921	15620	14552	14700	14948	386.92	7.00	11.67
1.0	15.0	14932	15625	14453	14709	14930	386.44	-18.50	-18.50
1.0	16.0	14933	15626	14453	14710	14931	386.46	0.75	0.75
1.0	17.0	14933	15626	14453	14710	14931	386.46	0.00	0.00
1.0	18.0	14933	15626	14453	14710	14931	386.46	0.00	0.00
1.0	19.0	14933	15626	14453	14710	14931	386.46	0.00	0.00
2.0	21.0	14933	15626	14453	14710	14931	386.46	0.00	0.00

PHOTOGRAPHS FROM FIELD AND LABORATORY EXPERIMENTS

Waste sorting and characterisation exercise at the waste transfer station of the UJ DFC


A bag of sorted food waste at the UJ DFC

Preservation of sampled feedstock

Monitoring of the anaerobic batch digestion setup by the investigator (candidate)

Oven drying for total solids' content determination

Furnace heating for volatile solids determination

The investigator (standing) presenting the project in a meeting with stakeholders from the campus’ occupational health department

The investigator (on the right) conducting a meeting and site visit with BiogasSA to study the Puxin digester

The proposed site near the Aurum ladies' residence for establishment of the project