Feasibility Study - Implementation of a Pilot Biogas Plant at Robinson Deep Landfill

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Executive Summary

The continued population growth alongside socio-economic changes have increased the need for improved mass transit as well as the waste generated within the City of Johannesburg (CoJ). The pressure on the available means of transport caused by geometrical increase in population and migration has increased the demand and consumption of fossil fuels and its consequent environmental impact. As available landfill airspace continues to reduce, waste generated within the CoJ have to be put into better use. This study is aimed at quantifying the potential of organic fraction of round collected refuse (RCR) and dailies (waste from restaurant) generated within the CoJ Municipality and Joburg Market's (JM) fruit and vegetable waste, discharged at Robinson deep landfill towards serving as substitute to fossil fuel for the CoJ metro buses. This report covers, in part, output 1 of the service level agreement (SLA) reached between the CoJ and the University of Johannesburg. The report entails the justification of choice of technology, waste quantification, characterization, biochemical methane potential analysis, energetic value of waste, preliminary design of plant and initial cost estimate.

The sections below present a summary of the findings with more descriptive details, provided in the body of the report.

1.0 Justification of Technology of Choice

Towards choosing the preferred waste to energy technology pathway, an analytical hierarchy process (AHP) was used for the multi-criteria decision analysis (MCDA) with environmental sustainability being the main goal of the decision. The criteria were environmental protection, sociocultural acceptance, technical depth and economic viability. Of the four alternative technologies investigated, anaerobic digestion is the most preferred with 54% acceptance in meeting the stated criteria with respect to achieving the main goal. Anaerobic digestion provides multiple ways of utilizing energy extracted from the process. The performance of other waste to energy technologies investigated were 27%, 14% and 5% for incineration, composting and landfilling respectively.

2.0 Waste Quantification

Waste quantification was conducted on site, at Robinson Deep Landfill from 29th October to 7th November, 2015 and the Johannesburg Market from 11 to 20th November, 2015. A total of 5.5 ton of waste was weighed, sorted and categorised at both sites (RCR 1.4 ton, Dailies 1 ton and JM 3.1 ton). The fractional composition of the waste from the three sources are presented Figure ES1, ES2 and ES3.

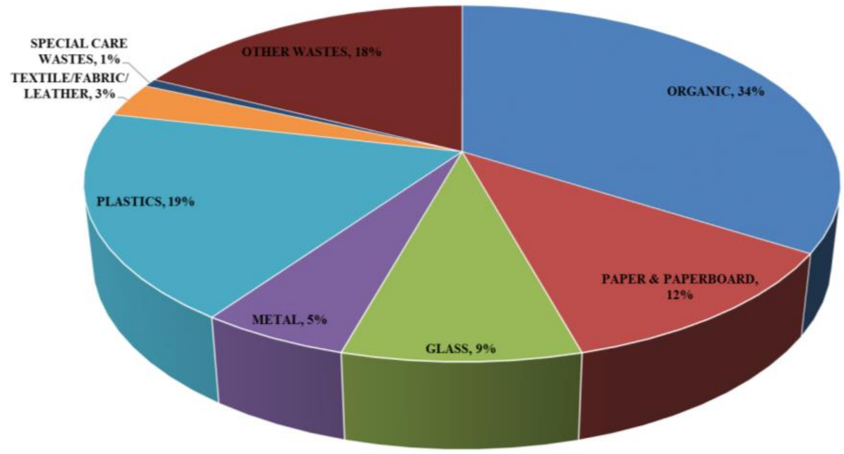

Figure ES1: Waste composition profile for RCR with 34% organic

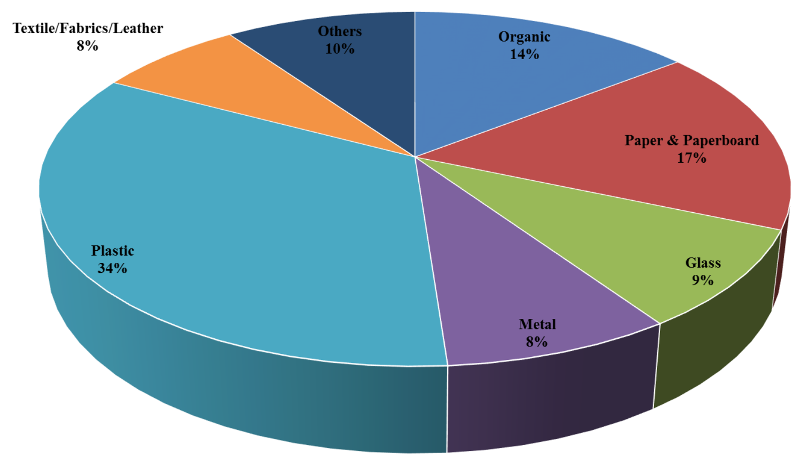

Figure ES2: Waste Composition profile for Dailies with 14% organic

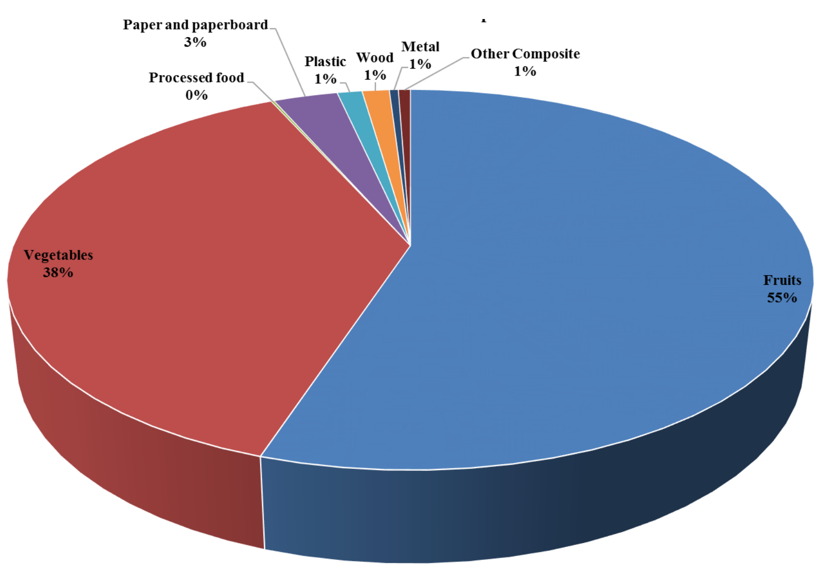

Figure ES3: Waste composition profile for JM with 93% organic

Due to non-functional weighing bridge at Robinson Deep Landfill during the study period, historical data were used to assess the daily tonnages of waste discharged. Based on historical data, an average total of 1,44,772 ton/year of waste is generated in the CoJ. Of this total, 562,028 ton/year is discharged at Robinson deep. The contributions of the stream of interest are 298,493 ton/year (817.8 ton/day), 8,655 (23.7 ton/day) ton/year and 18,213 ton/year (49.8 ton/day) for RCR, Dailies and JM waste respectively. Based on the quantification, the organic mass of the three waste sources is 327.7 ton/day. The contribution of the sources are 277.9 ton/day, 3.4 ton/day and 46.4 ton/day for RCR, dailies and JM waste respectively. Historical data for garden waste, a potential substrate for anaerobic digestion, was also recorded with about 168 ton/day. This put the total organic waste at 495.8 tons/day or 180,959 ton/year.

3.0 Theoretical Energetic Equivalence

If all organic fraction of waste is available for anaerobic digestion, a theoretical 14,096,057 m^3/year of biogas can be produced equivalent to 291,274 GJ/year. The annual biogas yield is equivalent to 8.4 million cubic meter of natural gas, 8 million litres of diesel, and 9 million litres of petrol. The theoretical annual CO_2 reduction when the waste is diverted for use is 124,327 tCO_{2eq}.

4.0 Waste Characterization

The waste characterization was conducted at the UJ laboratories. For Robinson deep, Mixed waste comprised of mainly RCR and Dailies. TS% for mixed and garden waste was 27.33 and 29.26%, with moisture content of 72.67% and 70.74% respectively. Mixed waste had C/N ratio of 14.56 while garden had 10.1. At JM, The VS (%TS) ranged from 40% for cucumber to 96% for potatoes. The average VS (%TS) for the sampled fruit and vegetable was 78% with a median of 82%. About 99% of substrates from JM had C/N ratio within the optimal ratio (10-30), with few (about 1% of substrates) being above the optimal. The highest C/N ratio of about 36.59 and 46.36% was observed in beans and pea respectively, indicating the lake of nitrogen from the substrates.

5.0 Biochemical Methane Potential Analysis (BMP)

The BMP analysis was used to assess the degree of degradability of sampled organic waste. The analysis was conducted at UJ using automated methane potential test system (AMPTS II) equipment. Initial result indicated a BMP of 310 m^3 CH_4/kgVS with average CH_4 concentration of 59.46 %. This gives a 510 m^3 biogas/kgVS. This preliminary result was due to the fact that some aspects of this experiment required a greater time frame for conducting them and repeated runs. Considering the different classes of waste to be investigated and the urgency of this report, some of the experiments are still ongoing. Updated result will be subsequently provided. The results obtained are sufficient to proceed to the next phase of design.

6.0 Digester Type and Upgrading Technique

MCDA was applied towards choosing the digester type and upgrading technique. The result for digester type indicated that the "complete mix continuously stirred anaerobic digester" is preferred with 78.5% preference to other anaerobic digester technologies. AHP was employed towards selecting the most appropriate upgrading technology suitable for the CoJ pilot plant. The goal of environmental sustainability was defined by four criteria. The performance of the alternatives are presented in Figure ES4 with membrane having 27.2% preference when pitched with other technologies. Absorption with 26.9%, adsorption 25.3% and cryogenic 20.6%.

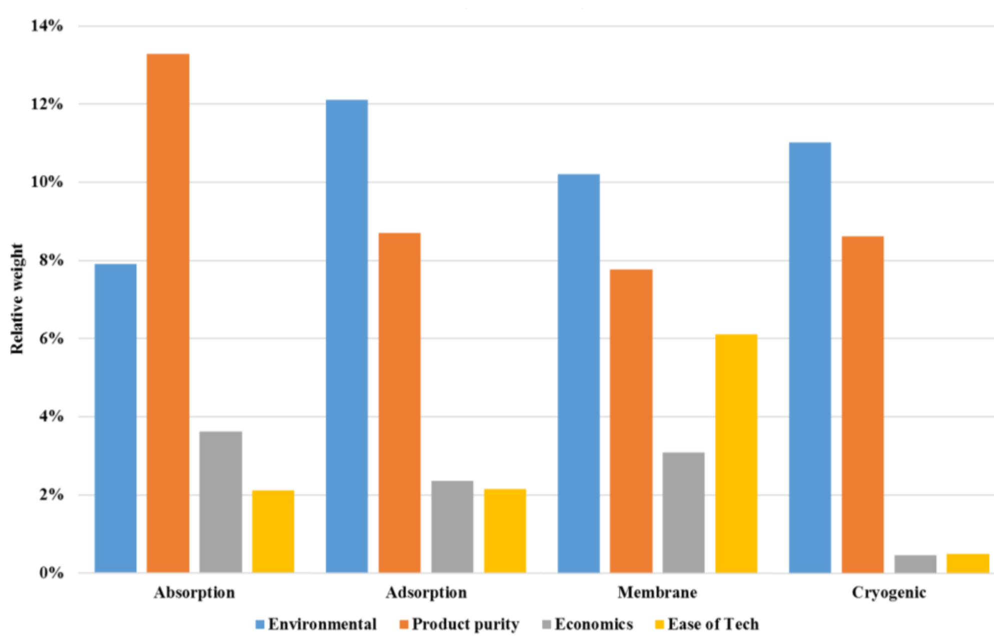

Figure ES4: Pairwise comparison of four upgrading alternative against four criteria

7.0 Plant Cost and Schematics

For the pilot study under consideration, a plant capacity of 10 ton/day is been proposed. The aim is to provide sufficient biomethane to fuel one metro bus per day at the worst driving conditions and engine performance. Based on interview with the general manager of the technical division of Johannesburg Metropolitan Bus Services (SOC) Limited, 100 l of diesel is required per day/bus. This is equivalent to about 107 Nm^3 of biomethane per day (140 Nm^3/day taking into account engine efficiency) when energy content is the variable for comparison. Based on the waste characterisation, BMP analysis, provision of sufficient fuel and improve economics of scale, a 10 ton/day plant capacity is being considered with a biomethane potential of 254 Nm3/day. Two digesters of 60m^3 and 300m^3, will be required amongst other plant peripherals. Based on detailed literature guided search, the whole plant cost (biogas production and upgrading) is estimated at $364,360 (R 6,199,050). The biogas production block flow diagram (BFD), upgrading process BFD and isometric projection of the plant are presented in Figure ES5, ES6 and ES7.

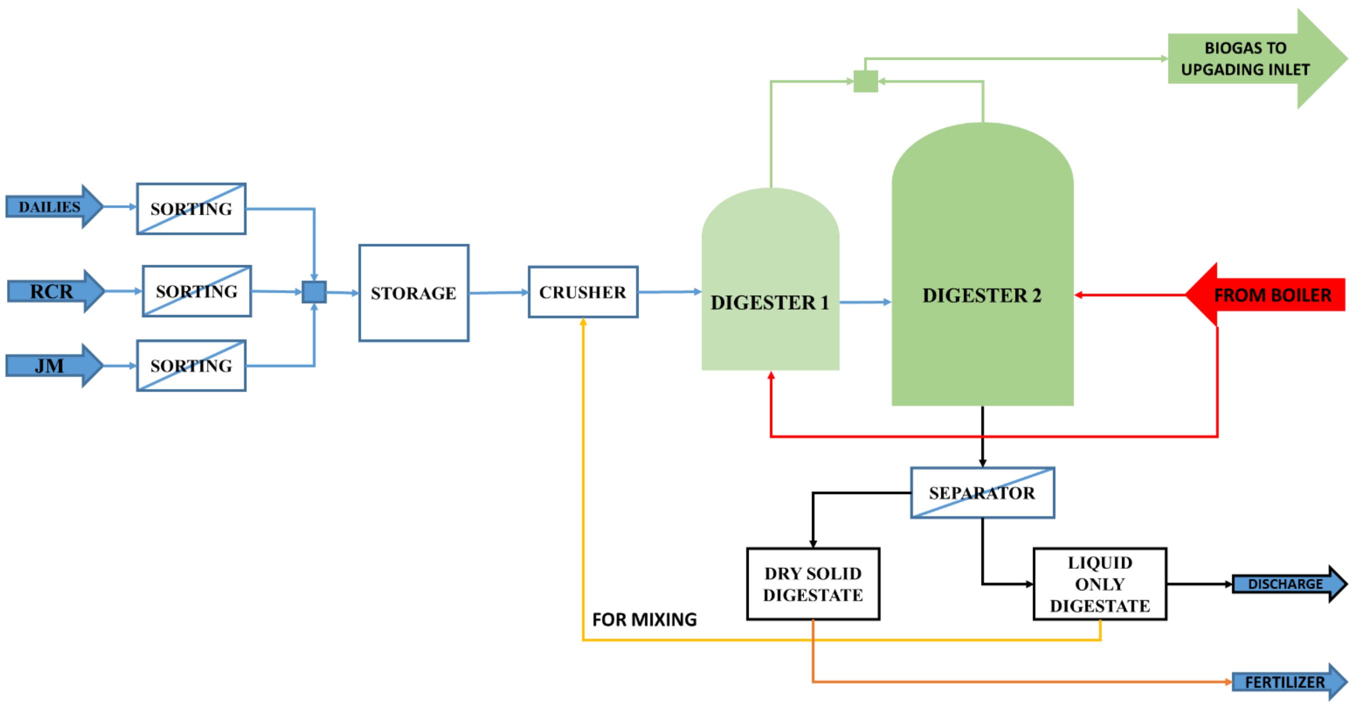

Figure ES5: Biogas production BFD

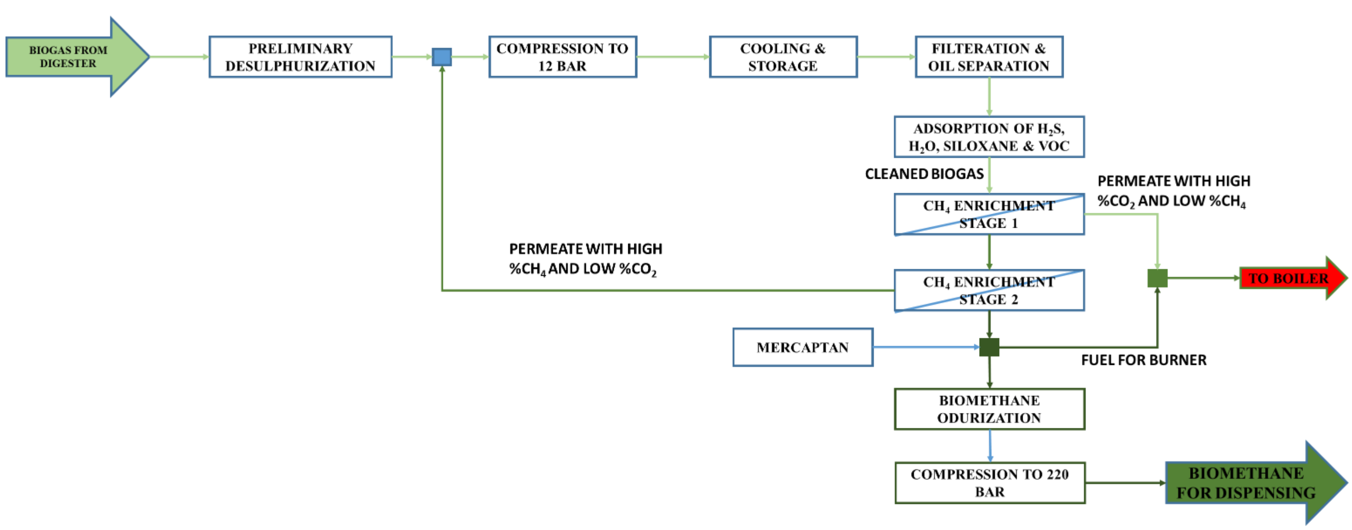

Figure ES6: Biogas upgrading BFD

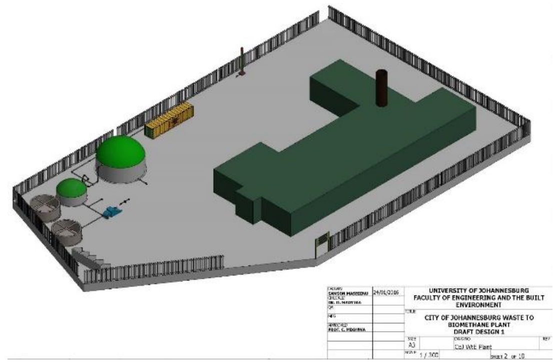

Figure ES7: Isometric projection of plant within the Incineration unit of Robinson Deep landfill

8.0 Findings and Recommendation

The following are the findings from the study conducted:

- The waste quantification conducted indicated that all organic waste discharged at Robinson Deep Landfill are available for energy recovery as they are presently being covered with top soil to degenerate
- 34% of RCR waste were organic while only 14% of dailies, mostly from restaurants, were seen as organics
- JM waste contains about 93% organics which are also available for energy recovery
- Chemical properties of organic waste analysed indicated wet anaerobic digestion is most suitable
- If all organic wastes are converted into biomethane about 20% of the CoJ’s 532 Metro buses can be fuelled, which is a conservative estimate.
- Sorting of organic fraction of RCR and Dailies will not cut jobs of exiting waste scavengers at Robinson deep as this class of waste is of no interest to them.

It is recommended that:

- High degree of sorting for RCR and Dailies is required to extract organic fraction of waste
- To reduce the task of sorting RCR and Dailies, awareness on source separation at household level is required
- Due to 93% of waste generated at JM been organic, which also require less sorting, anaerobic digestion of the whole waste should be considered in the near future
- To capture the actual tonnages of waste discharged at Robinson Deep Landfill, immediate commissioning of the weighing bridge should be prioritised.

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Glossary

AD	Anaerobic Digestion
AHP	Analytic Hierarchy Process
AMPTS	Automatic Methane Potential Test System
ASTM	American Society for Testing and Materials
BMP	Biochemical Methane Potential
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
CBG	Compressed Biogas
CHP	Combined Heat and Power
CH_4	Methane
COG	Centre of Gravity
CI	Consistency Index
CoJ	City of Johannesburg
C/N	Carbon Nitrogen Ratio
CO_2	Carbon Dioxide
CR	Consistency Ratio
CSTR	Continuous Stirred Tank Rector
DM	Dry Matter
DS	Decision Support
EU	European Union
GHG	Greenhouse Gas
GJ	Gallonjoule
H_2S	Hydrogen Sulphide
HCs	Hydrocarbons
HDPE	High Density Polyethelene
HRT	Hydraulic Retention Time
HW	Household Waste
ICE	Internal Combustion Engines
ISR	Inoculum to Substrate Ratio

JM	Joburg Market
JSE	Johannesburg Stock Exchange
LCA	Life Cycle Analysis
MBT	Mechanical biological treatment
MCDA	Multi- Criteria Decision Analysis
MJ	Megajoule
MSW	Municipal Solid Waste
N_2	Nitrogen
NaOH	Sodium Hydroxide
NGV	Natural Gas Vehicles
Nm^3	Normal cubic metre
NO_x	Nitrogen Oxide
NWMS	National Waste Management Strategy
O_2	Oxygen
OEM	Original Equipment Manufacturer
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate
PET	Poly ethylene terephthalate
PU	Pikitup
RCR	Round collected Refuse
RI	Ratio Index
RT	Retention Time
SLA	Service Level Agreement
SRT	Solid Retention Time
SSC	Sulphur Stress Cracking
TS	Total Solid
TTW	Tank to Wheel
UASB	Upflow Anaerobic Sludge Blanket
UJ	University of Johannesburg
VS	Volatile Solid
WtE	Waste to Energy
WTW	Well to Wheel

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1 Introduction

1.1 Project Description

The continued population growth alongside socio-economic changes has increased the need for mass transit and waste generated within the City of Johannesburg (CoJ). Historically, it's been documented that landfills have been the most common and convenient method of waste disposal. However, in recent years, there has been a clamour for alternative waste management systems as landfills are now seen as a short term solution due to its negative impact on the environment and human health. To effectively tackle greenhouse gas emission associated with urbanisation, and reduce waste discharged at landfill sites across the city, the reduction and reuse of waste, which include recycle and energy recovery, is currently been advocated for by the CoJ. The CoJ is mindful of rapid consumption rate of available airspace at her landfill sites under the existing waste management framework. Hence, CoJ is pioneering and funding the implementation of a waste to energy project (biomethane for vehicle fuel) to be sited at Robinson Deep Landfill, as a mitigating strategy to reduce the amount of waste discharged at the landfill and the associated emissions.

The University of Johannesburg (UJ) was appointed to coordinate all aspects of the project implementation. As part of its mandate, UJ has been commissioned to conduct a feasibility study to assess the biogas energy production potential of specific waste streams discharged at Robinson Deep Landfill.

1.2 Project Partners

1.2.1 City of Johannesburg (CoJ)

Johannesburg is the financial and commercial heart of South Africa. It is also one of the most powerful economic centres on the African continent. The cosmopolitan city shown in Figure 1-1 is located between latitude 26° 12' 08" S and longitude 28° 02' 37" E at an elevation of 1,767 m above sea level. It is the most densely populated and urbanised municipality in South Africa, home to over 3.8 million people. Urbanisation brings along with it increased waste generation and pollution if not well managed. The main drivers for improving waste management are public health and climate change. Towards developing a sustainable city, the CoJ listed a green bond, the first of any South African municipality, on the Johannesburg Stock Exchange (JSE) raising R1.46 billion bond to finance green energy initiatives such as biogas energy project and other green energy initiative aimed at reducing greenhouse gas emission. R234 million was set aside in the 2014/2015 financial year from the city operating budget to finance renewable energy and green initiatives.

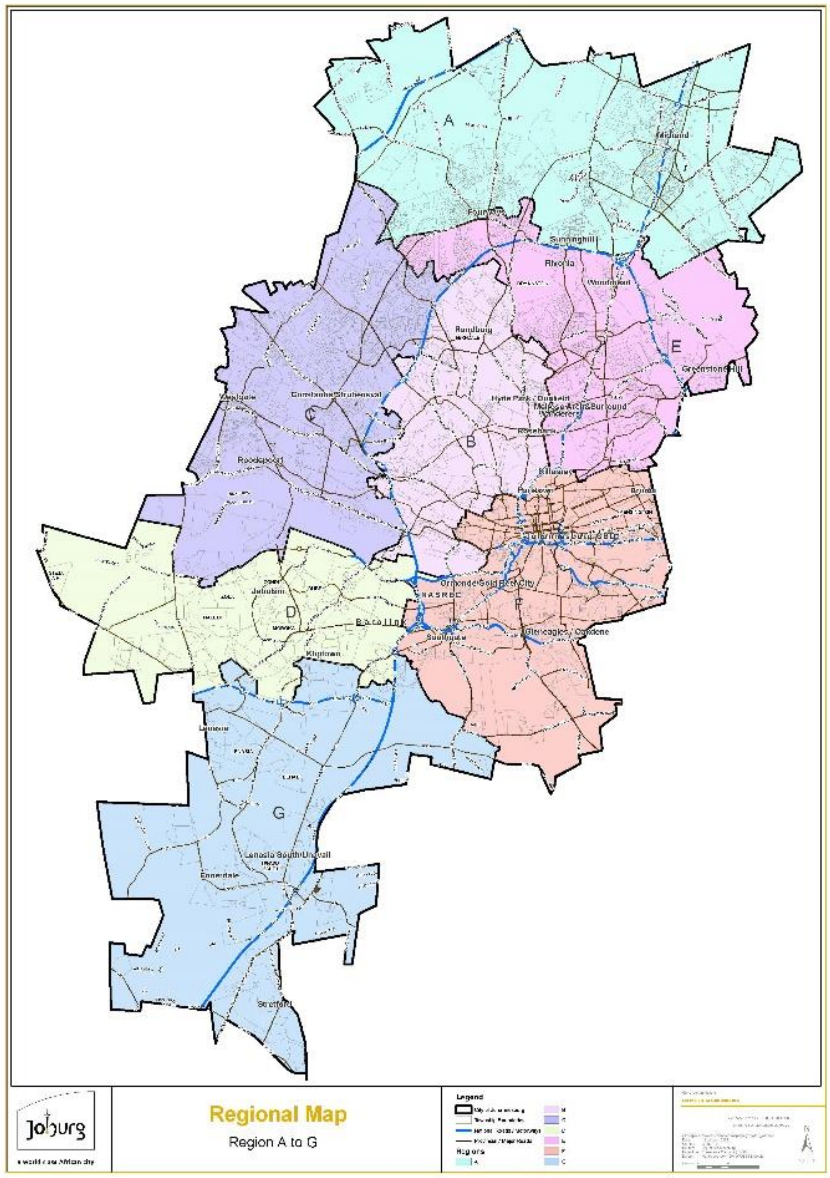

Figure 1-1 Regional Map of the City of Johannesburg

1.2.2 University of Johannesburg (UJ)

The UJ is a world class academic institution anchored in Africa. The UJ shares the pace and energy of cosmopolitan Johannesburg, the city whose name it carries. Proudly South African, the UJ is alive down to its African roots, and already shaping renewable energy initiatives within the continent of Africa impacting the global space with reduction in greenhouse gas emission. Due to UJ's vast scientific and technical knowledge capability, CoJ has commissioned UJ to deliver the waste to energy project using her skilled personnel and students. To this end, UJ is employing her "ReThink and ReInvent" philosophy to deliver on this project and creating a more sustainable way for waste management.

1.2.3 Pikitup (PU)

PU is the CoJ official waste management service provider, providing services across 1,645 km^2. PU's primary mandate is to provide sustainable integrated waste management to all residential areas, businesses, streets and open public places within the CoJ. PU operates 11 depots across the CoJ, manages 42 garden sites, one compost plant and 4 operational landfill sites. PU service 754,821 domestic customers, 9,658 business round collected refuse (RCR) customers, 1,270 bulk service customers, 906 dailies, 522 institutions and several compost customers[1]. Pikitup has embarked on several programs to minimize landfill waste in accordance with the National Environmental Management: Waste Act, 2008 (Act 59 of 2008), the National Waste Management Strategy (NWMS) and other related regulations. These efforts include the establishment of community recycling buy back centres and compositing sites.

1.2.4 Joburg Market (JM)

Joburg Market (JM), formerly known as Johannesburg Fresh Produce Market, is home to a large variety of fresh produce products serving about 5,000 farmers from across South Africa and budding entrepreneurs. Located 5 km South of Johannesburg's business district, it is the largest fresh produce market in South Africa and indeed Africa by volume. Fruit hub, potato and onion hub, and vegetable hub are the three trading hubs spanning over 65,000 m^2. JM is what keeps the CoJ human capacity going each day. JM is gfin a redevelopment phase of becoming "Market of the Future" aimed at creating a sustainable environment for effective management of produce and waste.

1.3 Project Aims

a) To prove the application, adaptability and scalability of enriched biomethane production from the organic fraction of municipal solid waste (OFMSW) in the CoJ.
b) To build capacity in the waste to energy technologies by knowledge generation and transfer of skills.

1.4 Project Deliverables

a) Feasibility study on the potential of organic fraction of municipal solid waste for use as fuel and in other high value applications.
b) Secure necessary authorisation and agreements for plant construction.
c) Detailed plant design.

[1] Pikitup 2013-2014 Integrated Annual Report

d) Transfer of knowledge through training and human capacity development.
e) Project implementation through an engineering, procurement and construction.

1.5 Feasibility Study Objectives

The objectives of the feasibility report are highlighted in accordance to Service Level Agreement (SLA) entered into between CoJ and UJ. They are;

a) identify, quantify and characterize the waste resources from JM and from Pikitup (dailies and bulk waste collections), with a view to determining the biomethane potential of these various waste streams.
b) identify high value utilization strategies and off-takers for the generated biogas
c) provide a comprehensive techno-economic study of the various process options and conversion paths for turning the targeted waste streams to enriched biogas
d) provide a comprehensive techno-economic study to determine optimal and most sustainable utilization of the enriched biogas produced at various scales.
e) develop a business plan inclusive of the various options for the city on the small, medium and large scale utilization of organic fraction of municipal solid waste for the production of biomethane, for use in high value applications such as mobility.

1.6 Approach to Feasibility Study

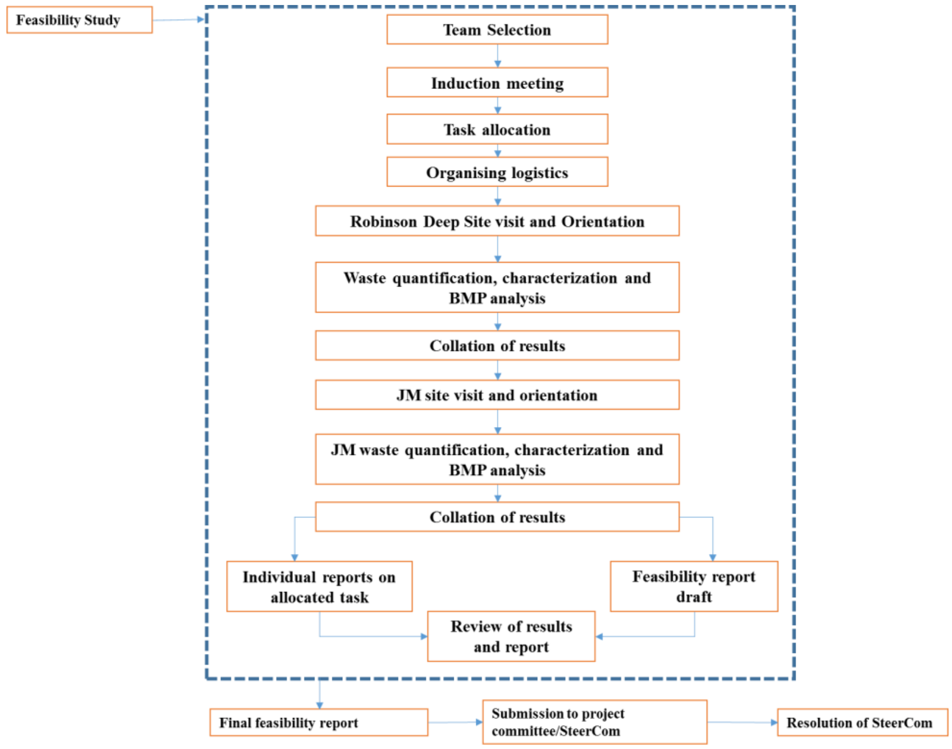

Figure 1-2 Approach to feasibility study

2 Problem Identification

The Kyoto convention signalled the world's acceptance of the damage it has caused to the environment through greenhouse gas emissions and it also ushered in the dawn of many countries taking the responsibility of cutting down on their carbon emissions. South Africa's carbon dioxide emission has continued to increase and in 2014, approximately *392,000 kilo tonne* of carbon dioxide was emitted, the highest in Africa. That seems low compared to what is emitted annually in China, USA and The European Union as shown in Figure 2-1 but South Africa's emission per capita which is a better representation of comparing emission index between countries as it divides the total carbon dioxide emissions by the total population is presented in Figure 2-2. South Africa has an emission per capita of 7.4 compared China's 7.6 and the EU with 6.7 with over 1.3 billion and 500 million people respectively. With over 4.4 million people living in the CoJ, the most populated city with in South Africa, the contribution of city to the overall emission is quite significant per square kilometre.

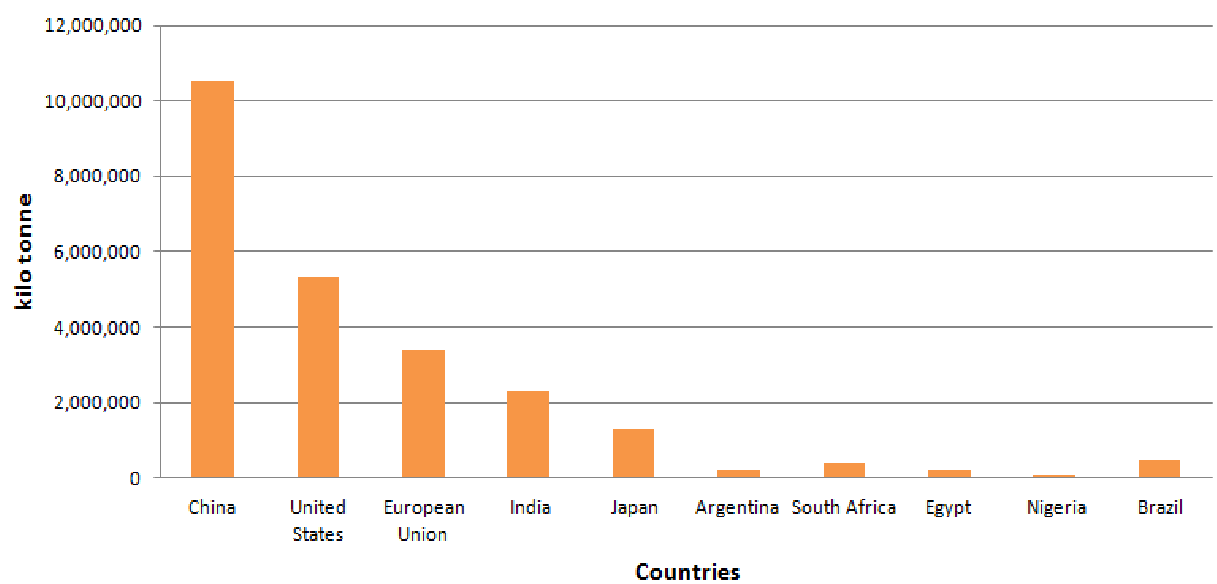

Figure 2-1 Carbon dioxide emission by countries

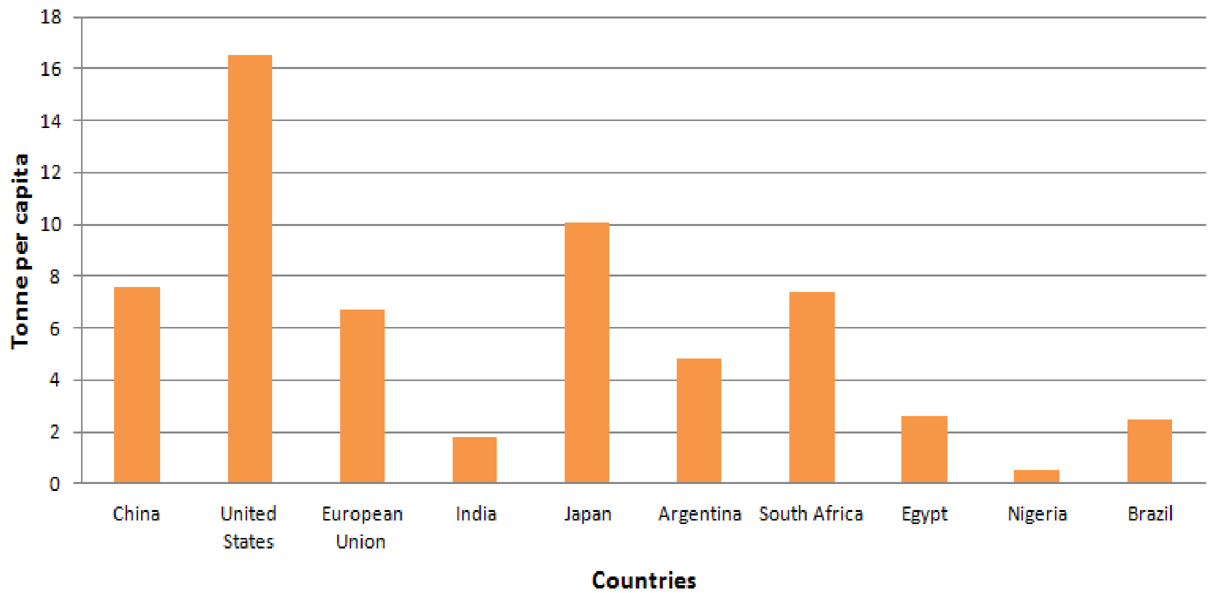

Figure 2-2 Carbon dioxide emission per capita

The CoJ generates about 1,444,772 ton of waste per year on average according to PU historical data as shown in Table 2-1. These wastes are discharged at four licensed landfills operated by PU. The landfills are; Robinson Deep, Marie Louise, Goudkoppies, and Emerdal. The waste is buried beneath layers of soil to allow natural decomposition as a means of destroying the waste. This is done continuously till the landfill reaches its capacity which is a function of the volume of waste a dedicated measure of land can efficiently hold when used as a landfill. Other factors that determine the lifespan are the depth of fill, rate of delivery, characteristics of solid waste, operating practices, soil properties, topographic information and recovery of capital investment to name a few. Designed capacity, utilized volume and life span of the four landfills are presented in Table 2-2.

Table 2-1 Historical Waste data

Ton/Annum	Robinson Deep	Marie Louise	Goudkoppies	Ennerdale	Ton/ann
2008-09	363,661	383,265	221,911	130,602	**1,099,439**
2009-10	521,417	334,616	295,716	114,363	**1,266,112**
2010-11	449,254	417,578	470,278	121,710	**1,458,820**
2011-12	594,261	512,798	428,669	127,108	**1,662,836**
2012-13	670,166	472,738	420,415	106,698	**1,670,017**
2013-14	773,409	320,688	326,016	91,296	**1,511,409**

Average (ton/annum)	**562,028**	**406,947**	**360,501**	**115,296**	**1,444,772**
Average (ton/day)	**1,539.80**	**1,114.92**	**987.67**	**315.88**	**3,958.28**

Table 2-2 Designed capacity, utilized volume and life span of landfills

	Robinson Deep	Marie louise	Goudkoppies	Ennerdale
Design capacity (m^3)	22,968,866	6,796,717	9,691,222	2,223,209
Available (m^3)	4,972,680	1,744,613	4,581,290	1,112,221
Utilized (m^3)	17,996,186	5,052,104	5,109,932	1,110,988
Life left (years)	7	6	15	13
Closure date (years)	May 2021	January 2021	January 2030	July 2021

	Robinson Deep	**Marie Louise**	**Goudkoppies**	**Ennerdale**
Design capacity (m3)	22,968,866	6,796,717	9,691,222	2,223,209
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Utilized (m3)	17,996,186	5,052,104	5,109,932	1,110,988
Life left (years)	7	6	15	13
Closure	May-21	Jan-21	Jan-30	Jul-21

Robinson Deep Landfill with the largest design capacity has about 7 years left of efficient utilization. The geometric increase in waste disposal associated with population growth, migration and consumerism, indicate that the airspace could be exhausted in less than 7 years. The health and environmental hazards coupled with the relatively short life span of the landfills have necessitated the need for more effective waste management systems which would not only render the waste innocuous but utilize the waste for productive outputs. These would reduce our dependency on landfills, where useful land mass and its resources, which would have been used for more productive purposes, are less efficiently used as dumpsites. Another point of note is that decommissioned landfills will continue to generate methane for 30-50 years which is an environmental hazard if not properly managed. Considering the utilized capacity, life span, strategic location of Robinson Deep Landfill to the city centre and most importantly the environmental impact, alternative waste management strategies needs to be explored.

3 Waste Management Alternatives

Municipal Solid Waste (MSW), a by-product of the lifestyle of urban dwellers, comprises of wastes from household, offices, restaurants, fruit and vegetable market and food processing industries among others. In some countries, construction wastes are also included as MSW but it excludes hazardous waste. MSW management encompasses the generation, handling, storage, collection, transfer, transportation, processing and final disposal of wastes. The management of MSW within the CoJ is of utmost concern as the volume of waste generated continues to increase along with population and economic growth. There are several obstacles confronting MSW management within the CoJ. Some of such obstacles are; interrelation of economic growth and urbanization; complexity of the waste stream due to different class of citizen living within the city; lack of adequate facilities that will expedite waste separation at source; overstretching of the superannuated infrastructure; and also the waste management technologies that are handy are very costly compared to the cost of land-filling. Currently, the CoJ in conjunction with PU are already implementing elements of the National Waste Management Strategy, in particular the waste hierarchy of avoidance, reduction, recovery, reuse, recycle, treat and dispose as summarised in Figure 3-1. Separation of waste at source or the use of waste transfer station have both achieved some degree of success and are ready for city wide roll out. However, the option of energy recovery as highlighted in Figure 3-1 after separation at source has not yet been implemented effectively.

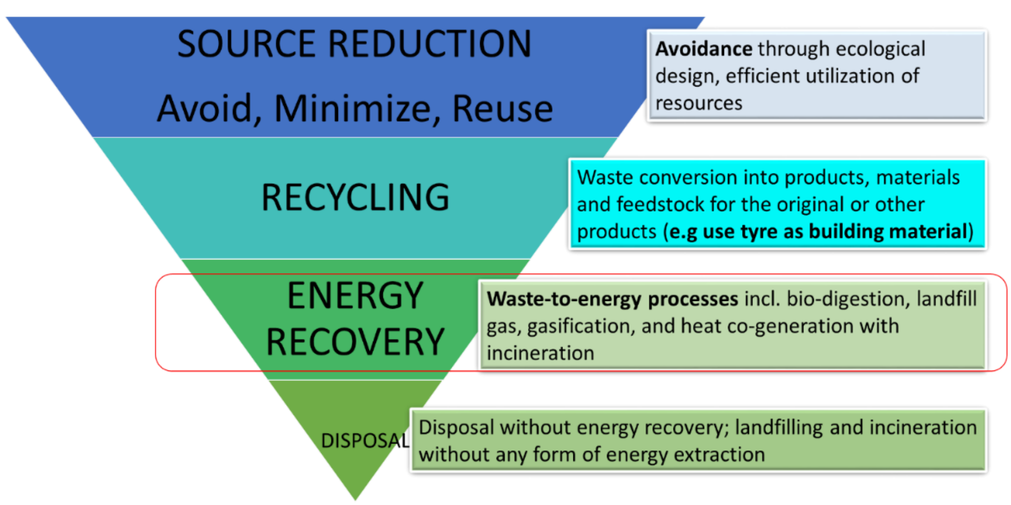


Figure 3-1 Summarised waste management hierarchy

3.1 Energy recovery from waste

The energy recovery technology from waste depends on the state of the waste, type of fuel needed and the composition of the substrate, but generally, thermal, biological and mechanical conversion processes are applied. The thermal conversion processes, which are very fast include: incineration; gasification;

liquefaction; and pyrolysis. Biological processes which are relatively slow and mostly suitable for organic fraction of MSW include; hydrolysis; fermentation; and anaerobic digestion. The mechanical process involves pressurised extraction. A short description of some of the technologies suitable for MSW management are described below;

3.1.1 Incineration

The main aim of incineration is to reduce volume, toxicity and reactivity of MSW. 90% volume reduction and 75% mass reduction are possible. However, it is not an absolute environmental solution due to the nature of its by-product; ash, flue gas and heat. The flue gas must be cleaned before they are released to the atmosphere. In advanced system, energy recovery is implemented alongside incineration. Waste management using incineration method is now a disputable disposal option in so many countries of the world owing to the hazard it poses to human health and the environment**.** The primary aim of MSW management is improving human health and reducing environmental impacts, both of which cannot be guaranteed through the adoption of incineration as a waste management technique.

3.1.2 Pyrolysis

Pyrolysis is the thermochemical decomposition of organic waste in the absence of Oxygen (O_2). This reaction takes places at operating temperature between 250-430 °C. In the course of this reaction, organic substance is converted to gases, liquid and solid residues which contain carbon and ash. When waste is decomposed through this process, recyclable products are produced. When the process is applied as a MSW management technology, carbonaceous char, oil and combustible gases are produced. The high temperature requirement of this process has negative environmental impact.

3.1.3 Gasification

Gasification is a thermochemical decomposition of MSW using a fraction of oxidizing agent. It could be described as the incomplete decomposition of carbon-based feedstock to generate synthesis gas. This process is close to pyrolysis; the only difference is that oxygen is included to keep a reducing atmosphere, where the amount of oxygen that is available is less than the stoichiometric ratio for complete combustion. Gasification produces syngas which are primarily carbon monoxide, hydrogen, and sometimes methane. They can be used for heat, power, fuels, fertilizers or chemical products and may produce char, inert slag, brine, bio-oils and steam. The residual char and slag may require landfilling. A Gasification facility often produces greenhouse gas, contaminants and toxins. Gasification equipment will require large quantities of residuals as feedstock which is about 75-330 tons per day.

3.1.4 Composting

Composting is a good alternative to transporting organic waste to the landfill, as it could be done on-site with minimal investment. The process produces fertilizer and heat. Also produced is carbon dioxide, a greenhouse gas, which is released into the atmosphere. There are high possibilities of contaminants such as glass in the waste to be composted which will render the produce product worthless.

3.1.5 Anaerobic digestion

Anaerobic digestion is the biological degradation of organic matter in the absence of oxygen. The process is suitable for energy recovery from different organic feedstock with biogas and digestate as the main product of the process. The biogas consists of mainly methane, a combustible gas, and carbon dioxide. The digestate can be utilised for different purposes. Depending on its characteristics, polymer products can be made from digestate aside it utilization as fertilizer. Anaerobic digestion stabilizes, disinfect and deodorise waste. It provides flexibility of use of fuel produced by this process.

3.2 Screening Waste-to-Energy (WtE) Technologies

An Analytic Hierarchy Process (AHP) was used in the decision making process for the most appropriate technology. The goal of the decision was to select the WtE technology with the lowest negative impact on the environment. Four key criteria were considered, they are; Environmental; Sociocultural; Technical; and Economic criteria. Each of the criteria has their sub-criteria that were used to conduct a pairwise comparison. Four WtE technology options were considered namely; anaerobic digestion, composting, incineration and landfill. A nine-point scale pairwise comparison was used in developing a comparison matrix table. Confidence level of result was checked using consistency index (CI) and consistency ratio (CR). A CR < 0.1 indicates that the analysis is reliable.

3.2.1 Results

A pairwise comparison on the criteria was conducted with a subjective approach based on the overall goal of the analysis, which is environmental preservation. The weighted factor for the four criteria is as presented in Table 3-1.

Table 3-1 Priority vector of the criteria

	Environmental	Sociocultural	Technical	Economical
Weighted factor	0.5527	0.2595	0.0538	0.1341

Pairwise comparison of each technology was conducted against each criteria and a priority matrix was developed. The performance of each WtE technology presented as a priority vector against the four criteria is summarised in Figure 3-2.

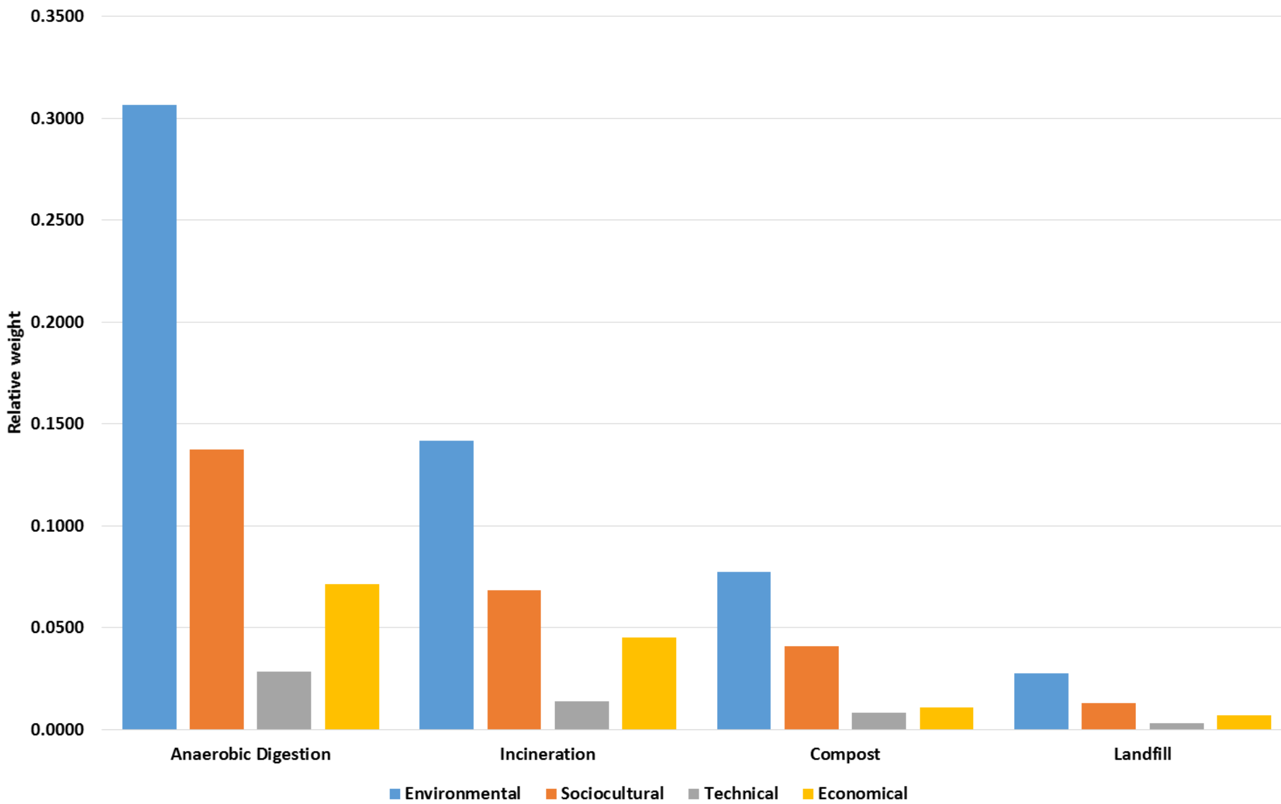


Figure 3-2 WtE technology ranking against each criteria

Synthesis of all matrices was done. Synthesis is the process of multiplying each criterion ranking by the priority vector and adding the resulting weights to get the overall priority vector. From Figure 3-3, there is a 54% acceptance of anaerobic digestion towards meeting the four criteria stated to achieve the goal of environmental preservation while landfill has the least acceptance of 5%.

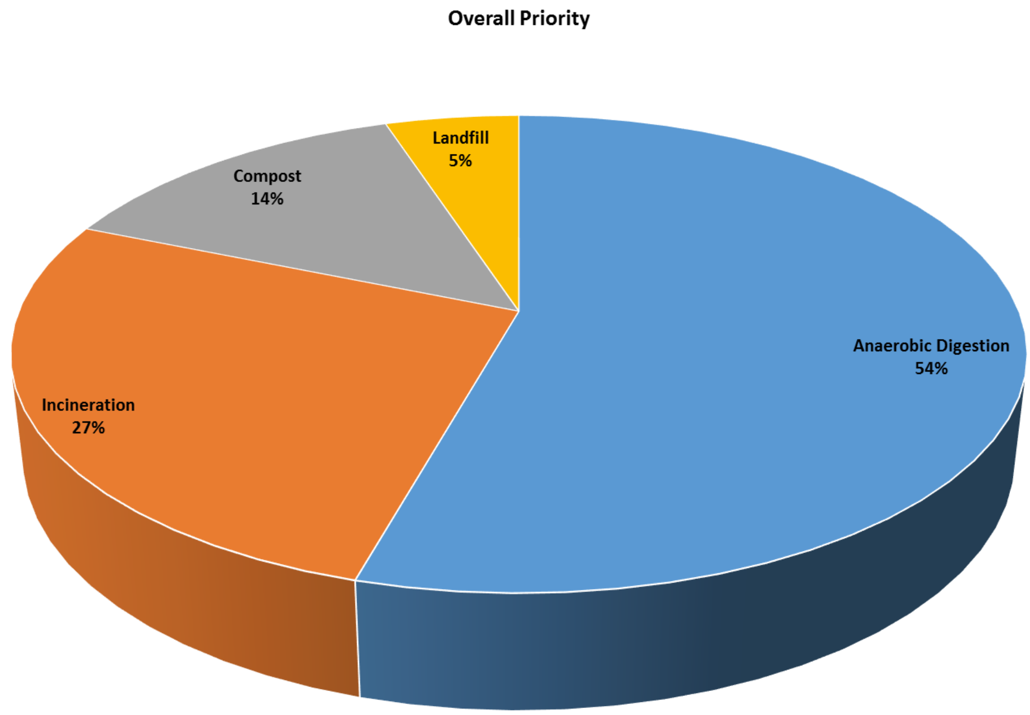


Figure 3-3 Overall priority of each technology towards the goal of environmental preservation

From Table 3-2, anaerobic digestion has the largest outcome. Idealizing the largest outcome and proportioning other technologies against anaerobic digestion, implies that incineration has a 49.42% of the appeal of anaerobic digestion, composting has 25.24% of the appeal of anaerobic digestion and landfill has the least appeal of 9.29% to anaerobic digestion. The overall CI, RI and CR indicated the analysis was reliable as overall CR<0.1 as shown in Table 3-3.

Table 3-2 Overall priority and idealized priority of each WtE technology

	Environmental	Sociocultural	Technical	Economical	Overall Priority	Idealized Priority
Anaerobic Digestion	0.3063	0.1375	0.0285	0.0713	0.5436	1.0000
Incineration	0.1416	0.0682	0.0139	0.0450	0.2686	0.4942
Compost	0.0772	0.0409	0.0082	0.0109	0.1372	0.2524
Landfill	0.0275	0.0129	0.0032	0.0069	0.0505	0.0929

Table 3-3 Confidence check of analysis

Overall CI	Overall RI	Overall CR
0.1478	1.8000	0.0821

From the MCDA-AHP results, anaerobic digestion is the most preferred technology, taking into consideration environmental preservation as the ultimate goal. Anaerobic digestion is only suitable for organic waste hence it has become very paramount to quantify the percentage of organic wastes that go into the waste streams which mostly end up at the landfills. The essential part of WtE project is the quantification of the waste streams. Waste quantification will assist in estimating the size and the functional units of the equipment that will be required for anaerobic digestion process. The procedures that are most frequently used to estimate the quantities of wastes are weight volume analysis, load count analysis and material balance analysis. Quantification is done by measuring weight of the wastes and volume of the containers and most times it is calculated in terms of mass which is normally measured in kilogram. Historical data are required to conduct a time series analysis and predict future trends of waste generation.

4 Waste Quantification and Characterisation

The initial step in the rational development of waste management, treatment and energy recovery using anaerobic digestion is to characterise the waste. Generally, a waste is characterised in terms of generation rate, physical properties, chemical composition and biological effects. Physical and chemical compositions of solid waste vary depending on sources and types of waste. The nature of deposited waste will affect the biogas production and composition by virtue of relative proportions of degradable and non-degradable components, the moisture content and the nature of the bio-degradable elements. Waste composition study will help the CoJ achieve the following;

- comply with national and international legislative on waste management
- identify baseline through which progress can be measured
- identify where cost and environmental efficiency can be impacted through few changes.

The data on quantity and quality of household waste (HW) gives information on the sustainability of developing cities. Reliable data on solid waste composition is required for waste management for resource recovery. Solid waste characterization provides information on how to tackle the issue of waste management. A clear idea of the characterization is necessary in order to define the reason for the characterization and to specify the method to be used. Some of the reasons may be to make data on waste quantities and composition available for use either in regional or national waste statistics as a premise for setting up policy on recycling or energy recovery. It may also be a means of grouping waste as either hazardous or non-hazardous in line with national regulation that will determine the set rules for the handling of waste. It helps to record how quality standard for recycled substances have been adhered to. It can also be used to measure the effectiveness of a recycled strategy by estimating the amount of recovered and non-recover waste items. The procedure employed to quantify and characterize the waste streams at Robinson Deep and JM described in the following sub-section.

4.1 Definition of the waste sources

4.1.1 Pikitup Round Collected Refuse

Round collected refuse (RCR) are the waste collected from all households and residents in the city, once a week. Various depot service neighbourhoods on a particular day of the week and the waste collected are discarded at the four landfill sites. This study only focuses on RCR discarded at Robinson Deep Landfill site.

4.1.2 Pikitup Dailies

Pikitup dailies are waste collected from restaurants and shop outlets within the city.

4.1.3 Joburg Market

All JM waste are discarded at the waste transfer station. The wastes are discarded in skips. These skips are evacuated daily to Robinson Deep Landfill. Due to the high perishability of this waste, their handling and disposal are quite critical for environmental acceptance.

4.2 Methodology for Waste Quantification

The waste characterisation study was carried out the Robinson Deep landfill site and JM by the UJ Research Team. The study was carried out in agreement with international standards. The standards are *ASTM - American Society for Testing and Materials - Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste (D5231 – 92 – 2008)* and *UNEP/IETC - Developing Integrated Solid Waste Management Plan, Volume 1, Waste Characterisation and Quantification with Projections for Future (2009)*. The exercise was conducted from the 29th of October to 7th of November 2015 (a period of 7 days) at the Robinson Deep Landfill site while it took place from the 11th to 20th of November (a 3-day site under-study and a 5-day quantification) at the JM in agreement with the standards.

Waste samples were collected and sorted manually for a period of two weeks both at Robinson landfill and JM. A sample of 100 kg of each waste stream was weighed as seen in literatures (ASTM D 5231-92). The activity ran through the week days from Monday to Friday. A sum of fifty-two (52) samples were analysed as stated in ASTM standard in order to provide statistical accuracy of 90% and confidence level. In this study, the waste samples were classified into nine broad groups for the characterization activity at Robinson landfill. At the fruits and vegetables market, the wastes were classified based on their species and colour. The total numbers of the fruits and vegetable species classification is 135 but not all were available due to the fact that they are seasonal. The nine groups for the Robinson landfill site characterization exercise were further sub-divided into fifty-two divisions. 100kg of each sample of waste was weighed, after collecting in refuse bins set aside for this activity. The UJ Research Team carried out the sorting, collection and characterization of the waste samples on site. Rear-End-Load (REL) Trucks of waste were sampled randomly and loads of wastes were discharged at designated area.

4.2.1 Equipment and Materials

The apparatus and materials that were used for the study comprise the following:

1. A crane scale with capacity of 500kg was used for weighing the waste samples.
2. Two heavy-duty tarps were spread on the ground and sorting of waste samples were carried out on them in order to prevent contamination of waste samples with the soil.
3. Earth moving equipment and shovels were used for thoroughly mixing of the wastes before samples were taken.
4. Three hand brooms were used to gather the residual waste samples after characterization.
5. Twenty one, 140 litre refuse bins were used with each labelled for the different waste type.
6. A wheelbarrow was used to convey the waste samples to the tarp.
7. Two large UJ branded canopies were used to provide shade during the analysis.
8. Traffic cones were used to demarcate the sampling and analysis areas to highlight our workspace and prevent moving trucks from invading our workspace.
9. First Aid kit was provided to attend to any medical emergency or minor accident
10. Personal Protective Equipment (PPE) were provided for all the team members which includes overalls, gloves, rubber boots, disposable face masks, helmets and safety goggles.
11. Hygiene supplies were provided (basins, liquid soap and disinfectants).

4.2.2 Procedure

In this study, the approaches that were used are as follows;

1. Discussion was carried out with the management of Robinson Deep landfill on waste composition and characterization study at the site and a procedural agreement was reached;
2. A region within Robinson Deep landfill was mapped out for the waste composition analysis and high visibility activity cones were utilized for boundary demarcation;
3. The outlined territory was a level surface and was near the tipping cell with the goal that it would not be difficult to transport the wastes;
4. The large tarps were spread on level surface within the mapped out area.
5. Each of the twenty-one waste containers was marked with the waste stream chosen for testing and was situated outside of the tarps.
6. Tare weight of each of the named containers were measured and recorded and it was occasionally rechecked.

7. The scale was placed at the encompassing region and level ground surface.
8. The scale's accuracy was checked via calibration. Occasionally a known (reference) weight was utilized to validate the accuracy of the scale.
9. 100 kg of mixed waste sample was taken and weighed.
10. Details of the source and kind of every waste specimen were analysed and recorded in tabular form on the waste composition data sheet developed by the team.
11. Details that were recorded on the form are date of sampling, time of sampling, vehicle details, origin of the wastes and the climate conditions.
12. The 100 kg waste samples were discarded on the tarpaulin for sorting.
13. Team members sorted the waste and classified them accordingly. Weight of the classified waste was measured and the total classes were summed up.
14. Each container had its content discharged and isolated.
15. Sorting of waste samples proceeded until the most extreme molecule size of the remaining waste particles giving about 20 mm and thereafter the remaining particles were transferred into the container designated for that waste segment.
16. After the sorting, every waste subcategory was put in the container labelled accordingly.
17. The gross weights of the wastes and storage containers were recorded on the endorsed form.
18. Data was recorded on the waste composition sheet as Compacted Round Collection Refuse (RCR), and Dailies Non-compacted wastes.
19. Gross weights of the wastes and containers were also recorded at the fruits and vegetables market.

4.3 Images from Site Activities

Images from both Robinson Deep and JM during the two weeks quantification

1

Landscape view of Robinson Deep

UJ Team Tent set-up

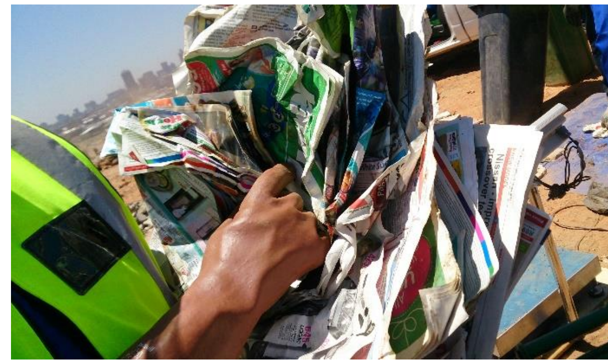
2	 Grading of allocated waste discharging point for the team	 REL Discharging Compacted waste
3	 Tarpaulin for waste sorting	 Some Members of the UJ team
4	 Waste sorting	 Waste sorting
5		

Labelled containers for different waste classes

Clearing up sorted waste

6

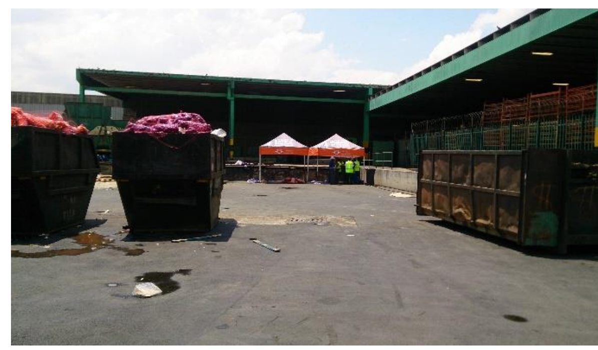
Sorted organic waste



Sorted papers

7

Weighing of sorted and classifed waste



UJ team at Joburg Market

8

Typical waste stream in skip

Sorting of JM waste

9

Random waste sample collection at JM

Wheeling samples for weighing

4.4 Results

4.4.1 Round Collected Refuse (RCR)

The results of the study carried out at the Robinson landfill site between 29th October and 6th November 2015 are presented in Figure 4-1 for Round Collected Refuse (RCR).

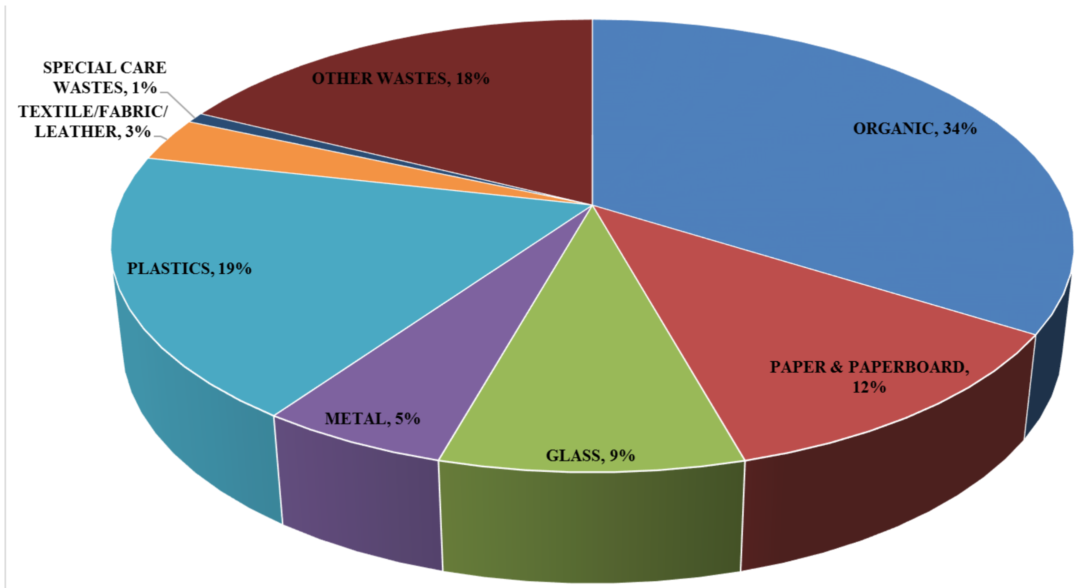


Figure 4-1 Municipal solid waste composition for RCR at Robinson Deep

Organic waste accounted for the highest percentage with 34% by weight while the least, 1%, was special care waste that included paints and artefacts waste. Construction and demolition waste were not found in all RCR sampled. The main components are further sub-divided as represented below.

4.4.1.1 Organic Wastes

Organic wastes had the highest percentage of 34% within the main components of the waste streams. In the subclass of organic waste, 58% was food waste as shown in Figure 4-2.

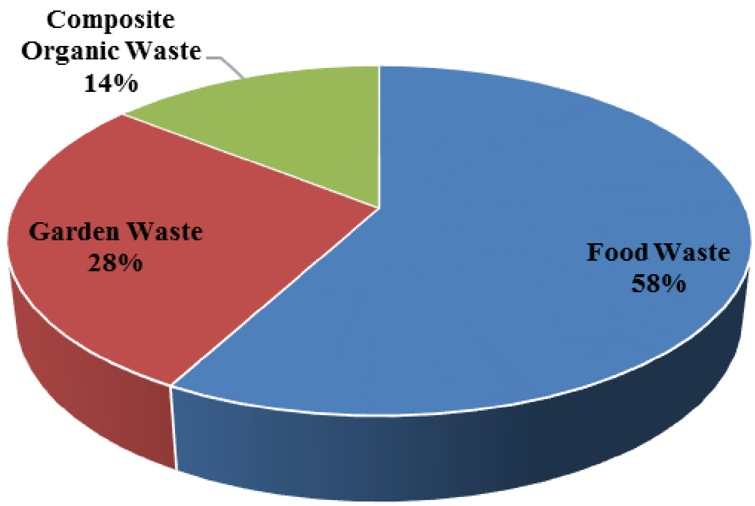


Figure 4-2 Composition of the organic waste

It was observed during the exercise that organic wastes are not being recycled. The scavengers only reclaim the inorganic wastes while the organic wastes are compacted and covered with soil. The total organic waste discharged at Robinson deep is available for energy recovery.

4.4.1.2 Plastics

Plastics had the second largest percentage about 19% of the total waste streams. Within the plastics subclass, 25% were clear PET, contributing the highest plastic waste while film plastic waste, the least was less than 0.1% Figure 4-3. It was observed during the exercise that most of the plastic waste were been reclaimed by scavengers and thus recycled.

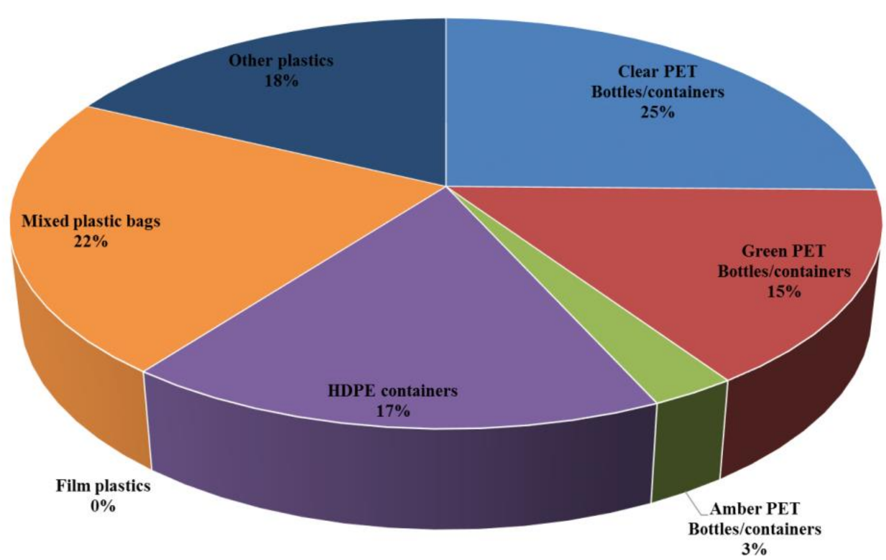


Figure 4-3 Composition of plastic waste

4.4.1.3 *Unclassified (also called Others) Wastes*

The unclassified waste is the third largest group, contributing 18% of the overall waste streams. Within this subclass of waste, diaper/sanitary products contributed 35%. The other waste composition of this subclass is presented in Figure 4-4. During the quantification exercise, not all waste within this category was recycled. Except for rubber, wood, and polyurethane foam, others are left for landfilling.

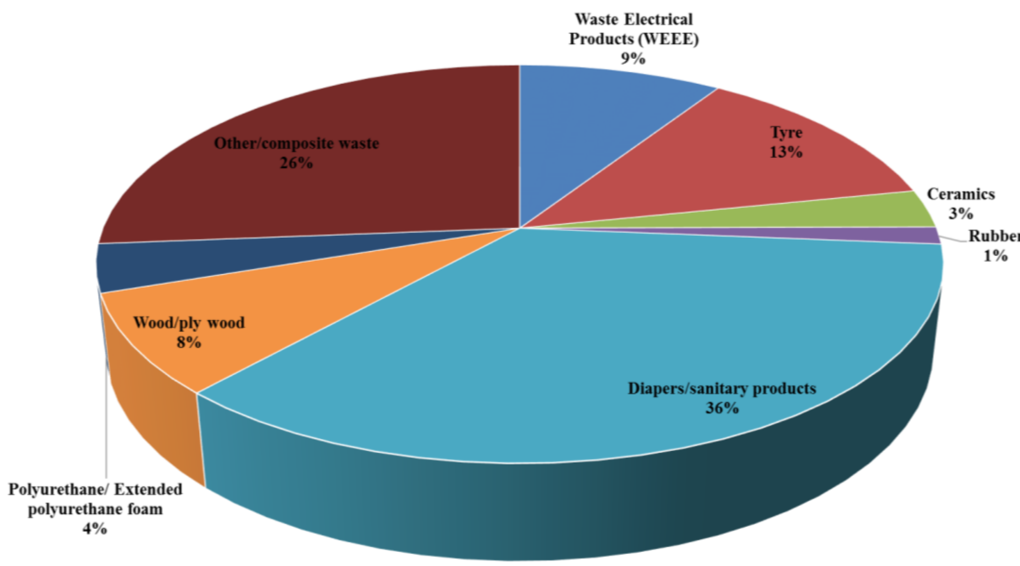


Figure 4-4 Composition of unclassified waste

4.4.1.4 *Paper and Paperboard*

Paper and paperboard occupied about 12% within the main components of the waste streams. Of this subclass, corrugated paper contributed 43% while books only contributed 1% as shown in Figure 4-5. There was no indication of paper and paperboard being recycled at Robinson Deep Landfill.

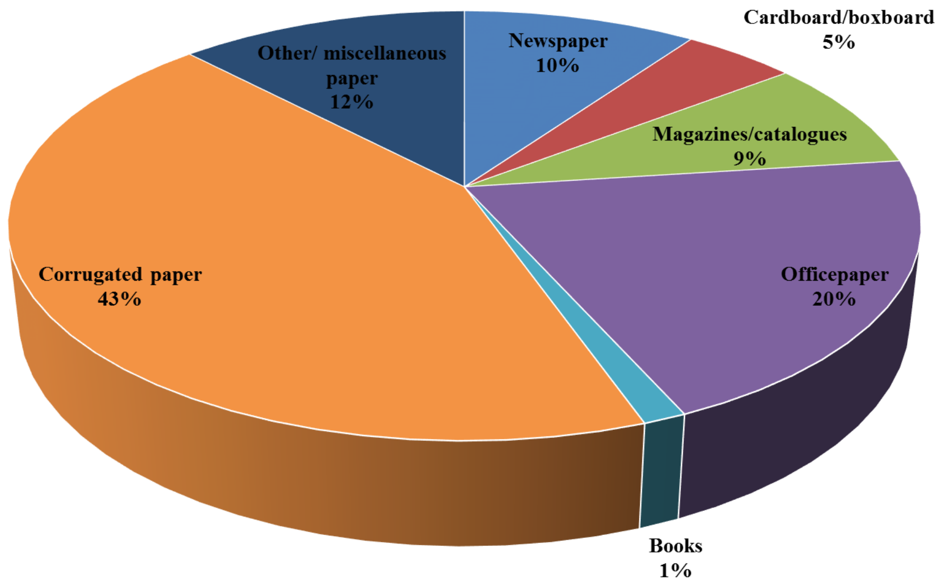


Figure 4-5 Composition of paper and paperboard waste

4.4.1.5 Glass

Glass occupied about 9% of the main component of the overall waste streams. Of the glass subclass, clear container bottles contributed the higher share of 71% as shown in Figure 4-6. There was no clear evidence if bottles were being recycled.

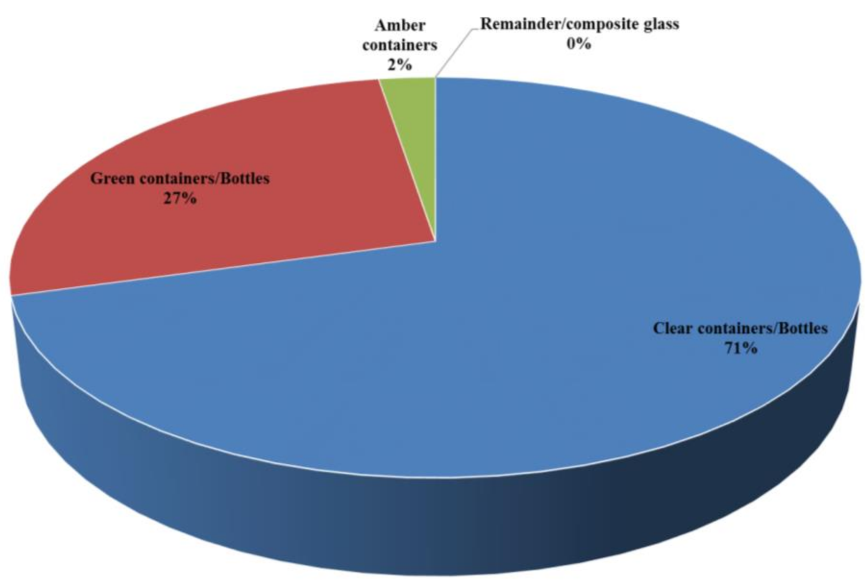


Figure 4-6 Composition of glass waste

4.4.1.6 Metal

Metals occupied about 5% of the main component of the overall waste streams. Aluminium container contributed 66% of this subclass of waste metal as shown in Figure 4-7. Almost all waste streams in this category are been reclaimed and recycled.

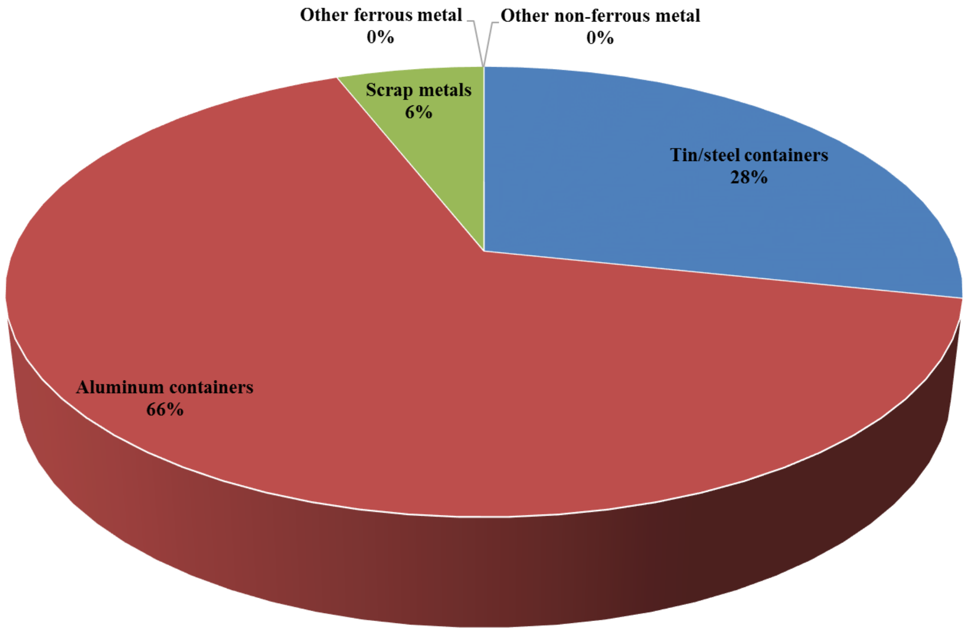


Figure 4-7 Composition of metal waste

4.4.1.7 Textiles

Textiles occupied about 3% of the main component of the overall waste streams. 58% of this subclass was clothing materials as shown in Figure 4-8. During the waste quantification exercise, there was no clear evidence that this class of waste were been recycled.

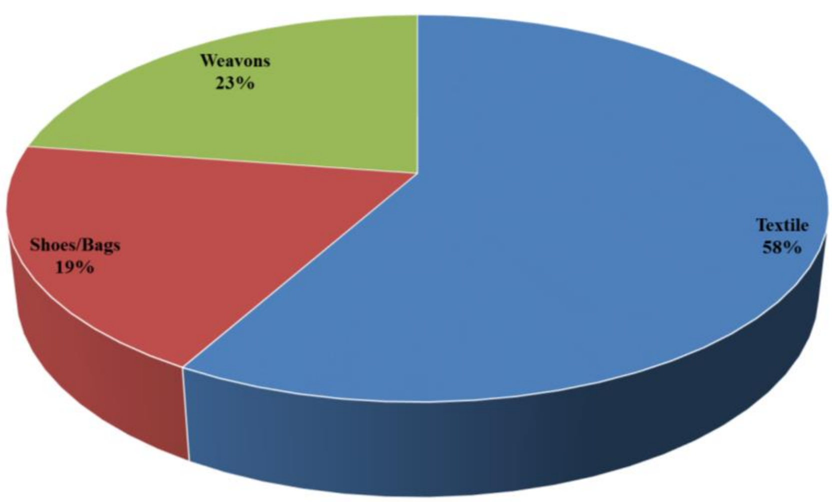


Figure 4-8 Composition of textile waste

4.4.1.8 Special Care Wastes

Specials care wastes occupied about 1% of the main component of the entire waste streams. Biomedical waste which account for 22% of this category include include medication, bandages and syringe. Oil filter for vehicle and paint container also contributed 21% and 9% respectively. Waste which could not be identified were classified and referred to as remainder/composite special waste as shown in Figure

4-9. During the quantification exercise, it was observed that only paint containers were reclaimed while other wastes in this category were not recycled.

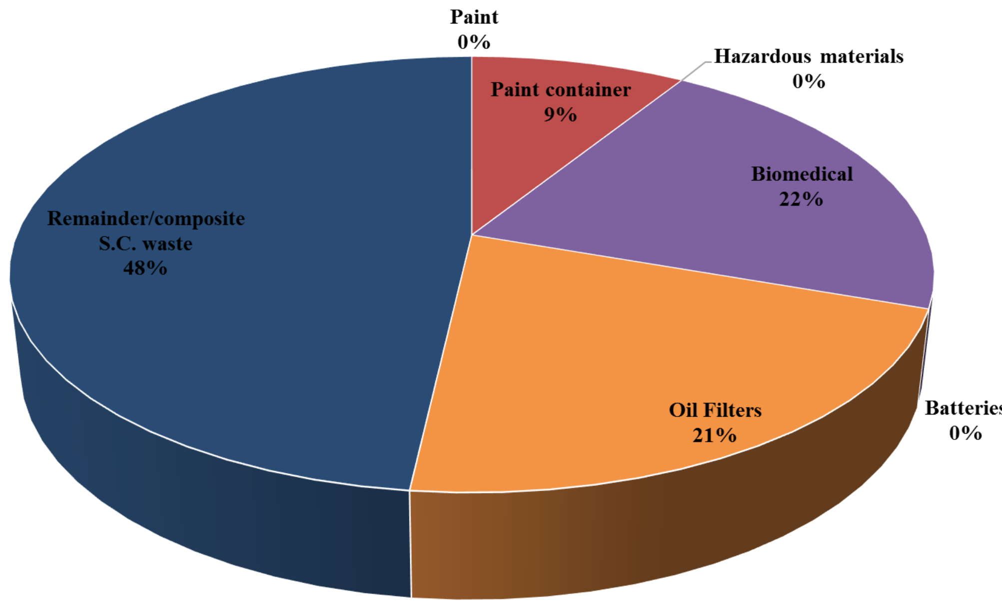


Figure 4-9 Composition of special care waste

4.4.2 Dailies Non-compacted MSW Results

The results of waste composition study conducted at Robinson landfill site from 29th October to 6th November 2015 for dailies non-compacted wastes are represented graphically in Figure 4-10.

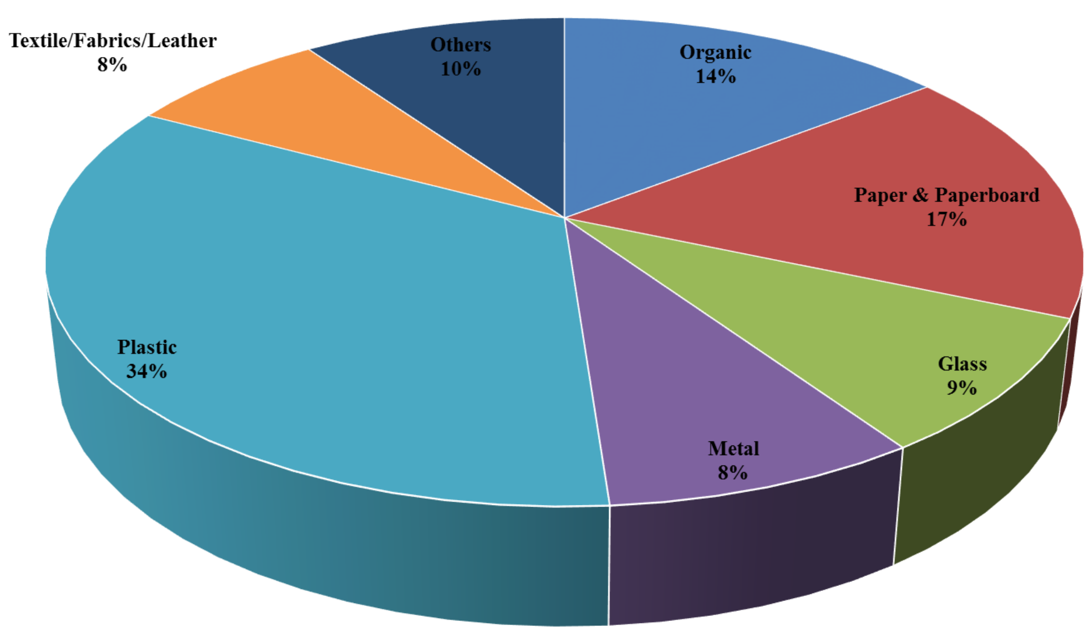


Figure 4-10 Composition of Dailies non-compacted waste

Organic waste only contributed 14% of the dailies. The highest contributor was plastic waste which accounted for 34% by weight. Paper and paperboard, glass and metal had a sizeable contribution as shown in Figure 4-10. The main components are further divided as shown in the following charts.

4.4.2.1 Plastics

Plastics cover 34% of the main component of the entire waste streams of the dailies source of waste. Of the plastic subclass, HDPE accounted for 28% as shown in Figure 4-11. Plastic bag and clear pet bottles also had a significant contribution of 24% and 21% respectively. In this subclass, just as observed in the RCR waste source, film plastic contribution was insignificant. A large percentage of the waste in the subclass is presently been reclaimed by scavengers and hence recycled.

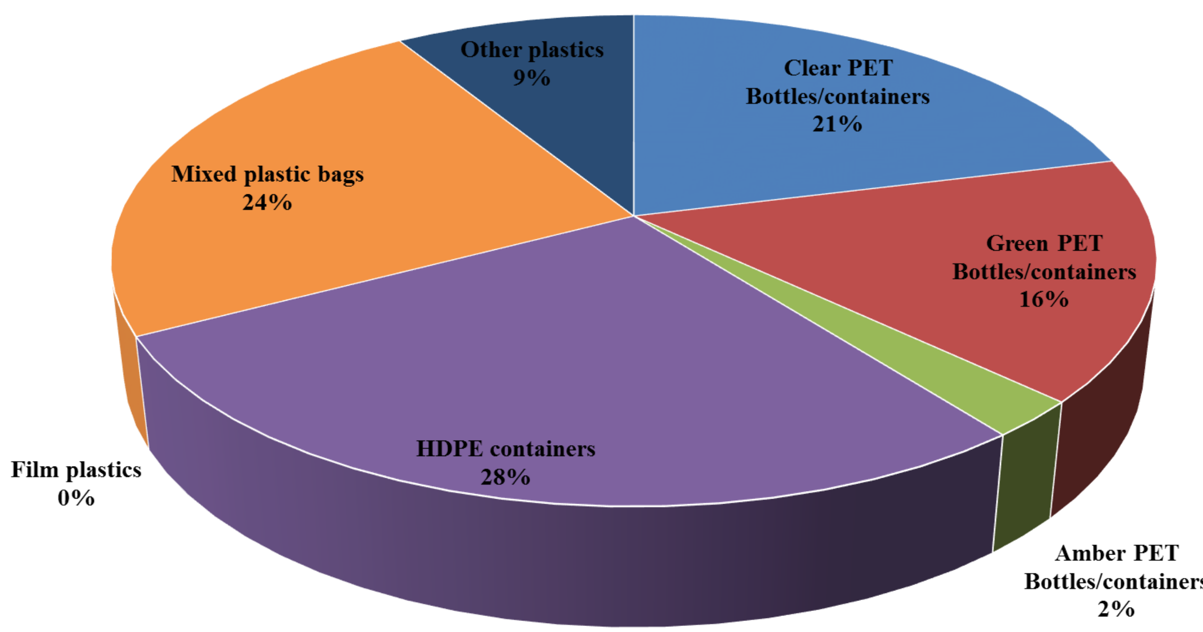


Figure 4-11 Composition of plastic waste for dailies

4.4.2.2 Paper and Paperboard

17% of the total dailies waste stream is made up of paper and paperboards. Of the class of waste, newspaper and cardboard contributed 28% and 21% respectively as shown in Figure 4-12. Paper that cannot be easily categories are referred to as others and contributed 32% of the total paper waste. There was no indication that papers are recycled at the landfill.

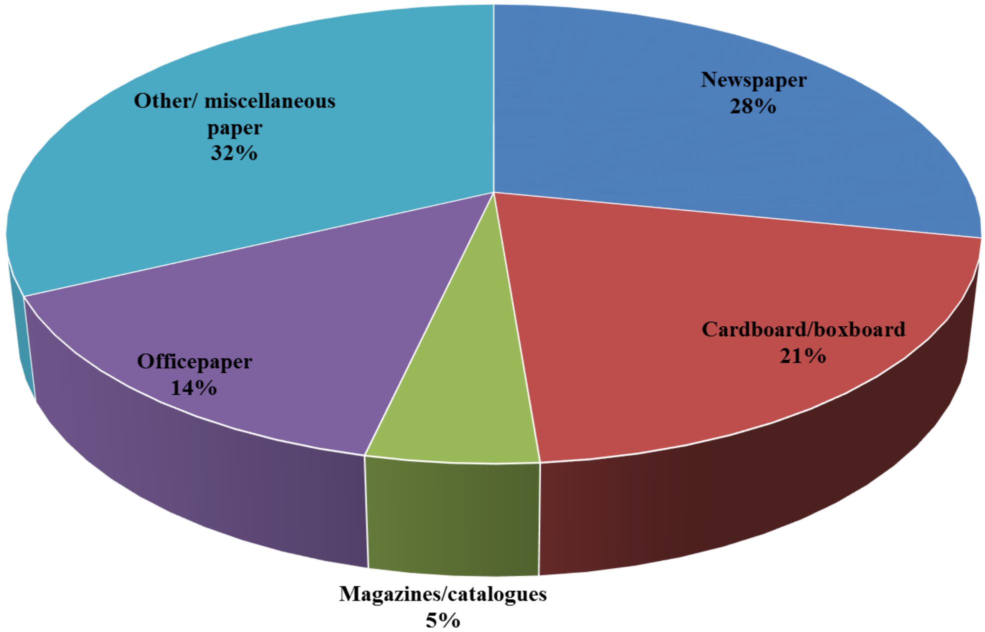


Figure 4-12 Composition of paper and paperboard waste streams for dailies

4.4.3 Organic wastes

Organic wastes covered 14% of the main component of the overall waste streams of dailies non-compacted MSW. 96% of this waste stream is food waste as shown in Figure 4-13. Organic wastes are not recovered; they are only compacted and covered with soil. Maximising the energy potential of this waste is of importance.

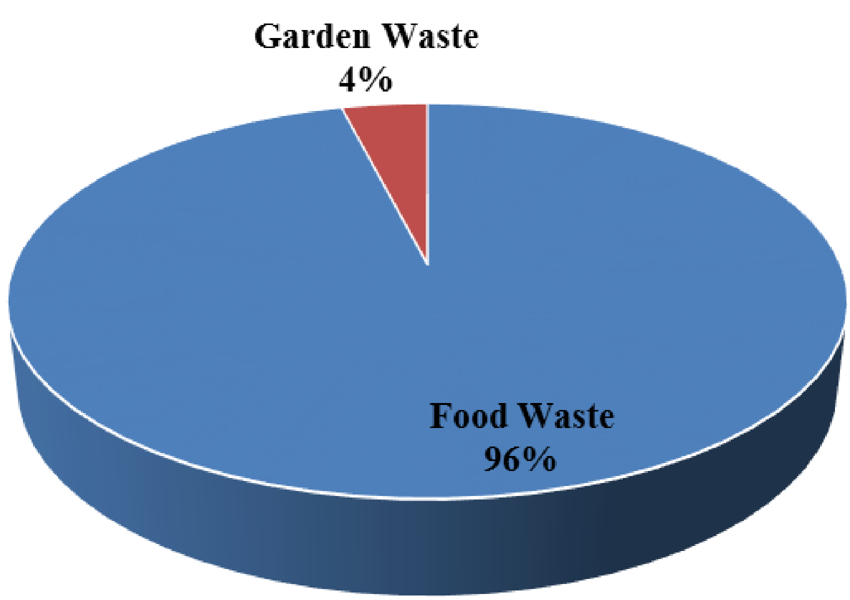


Figure 4-13 Composition of organic waste for dailies

4.4.3.1 *Other Wastes*

Other wastes occupied about 10% of the main component of the waste streams. Of this subclass, diapers/sanitary product and electrical product waste contributed 20% and 12% respectively as shown in Figure 4-14. All of diapers/sanitary product and some of electrical and composite waste are been compacted. Hence there is a partial recycling of some of the waste stream.

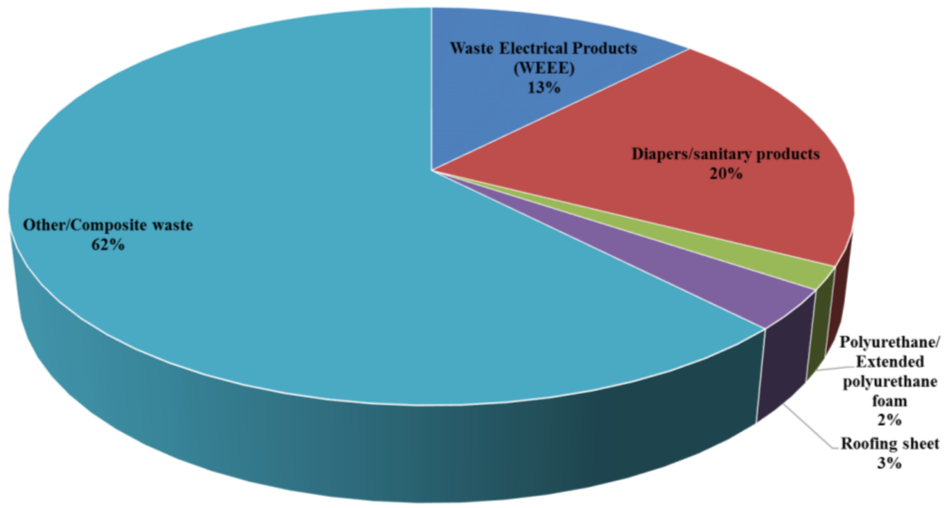


Figure 4-14 Composition of unclassified waste for dailies

4.4.3.2 *Glass*

Glass makes up 9% of the overall main component of the dailies. Of this subclass, clear container bottles contributed 61% as shown in Figure 4-15. There was no clear evidence that glass is recycled throughout the period of the exercise.

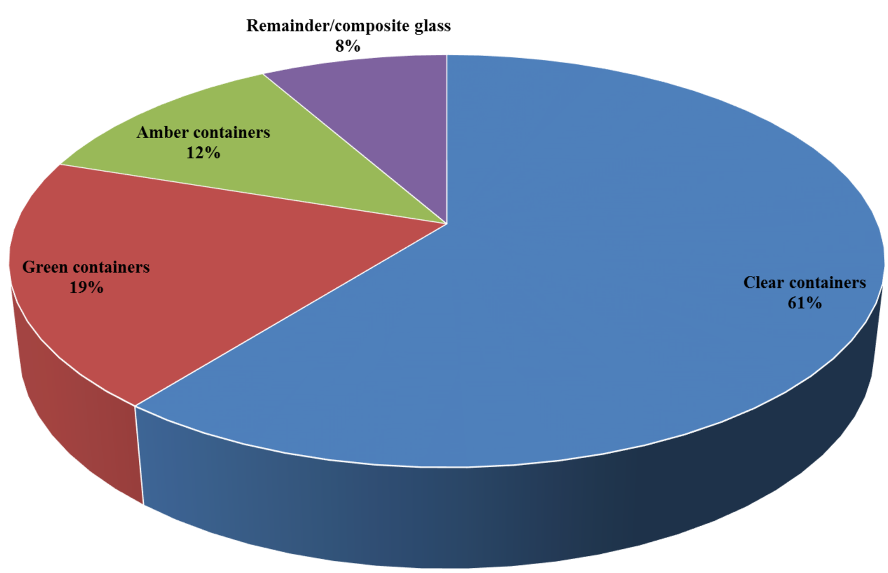


Figure 4-15 Composition of glass waste of dailies

4.4.3.3 Metal

Metal filled up 8% of the overall main component of the entire waste streams. 48% of the waste in this class was tin/steel containers. Aluminium contributed 38% as shown in Figure 4-16. The entire wastes in this category are recycled.

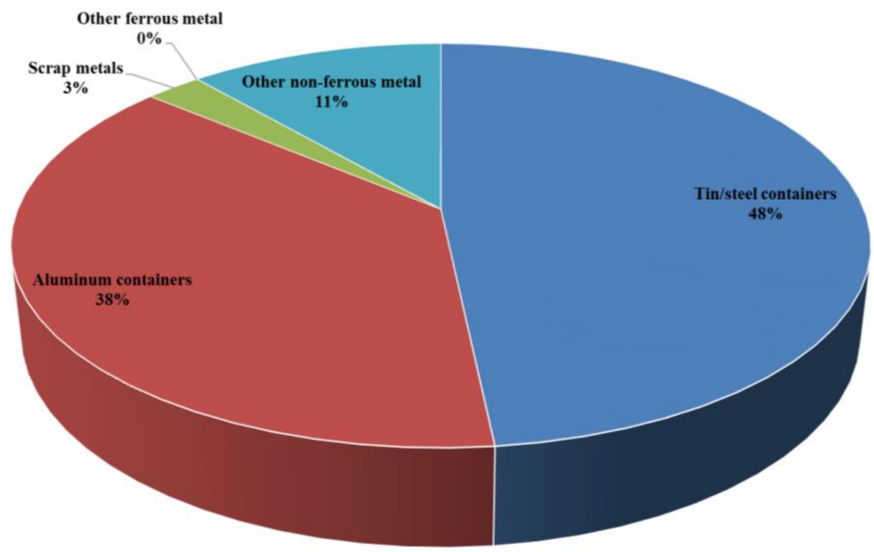


Figure 4-16 Composition of metal waste of dailies

4.4.3.4 Textiles

Textiles also occupied 8% of the main component of the overall waste streams of the daily non-compacted MSW. Within textiles category, weaves covered the largest percentage of 58% by weight, textiles occupied 36% and shoes and bags occupied 6% as shown in Figure 4-17. There was no any clear indication that any of the waste in this category was recycled throughout the period of the exercise.

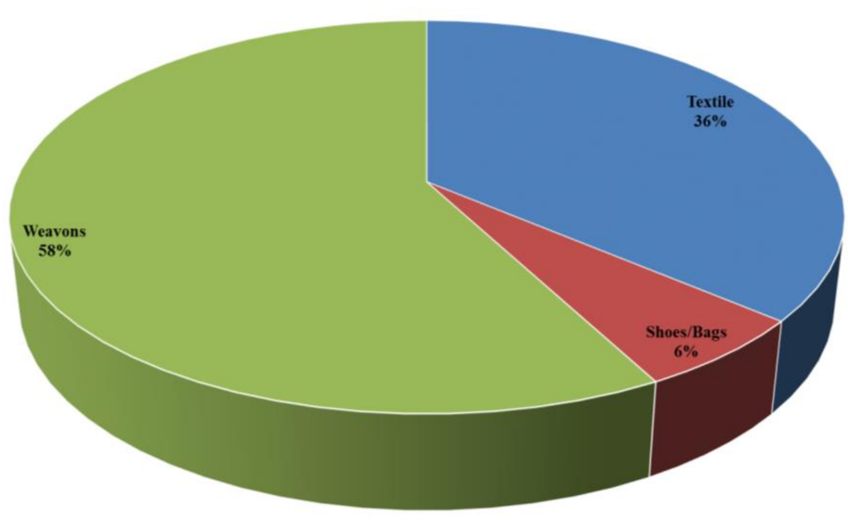


Figure 4-17 Composition of textile waste of dailies

4.4.4 Johannesburg Fruits and Vegetables Market Waste Composition Study

The results of the composition study carried out at the Fruits and Vegetables Market in the City of Johannesburg in November 2015 are represented in tabular form and graphically as shown in Table 3 and Figure 19. The main component is further divided into different categories as shown in the following charts;

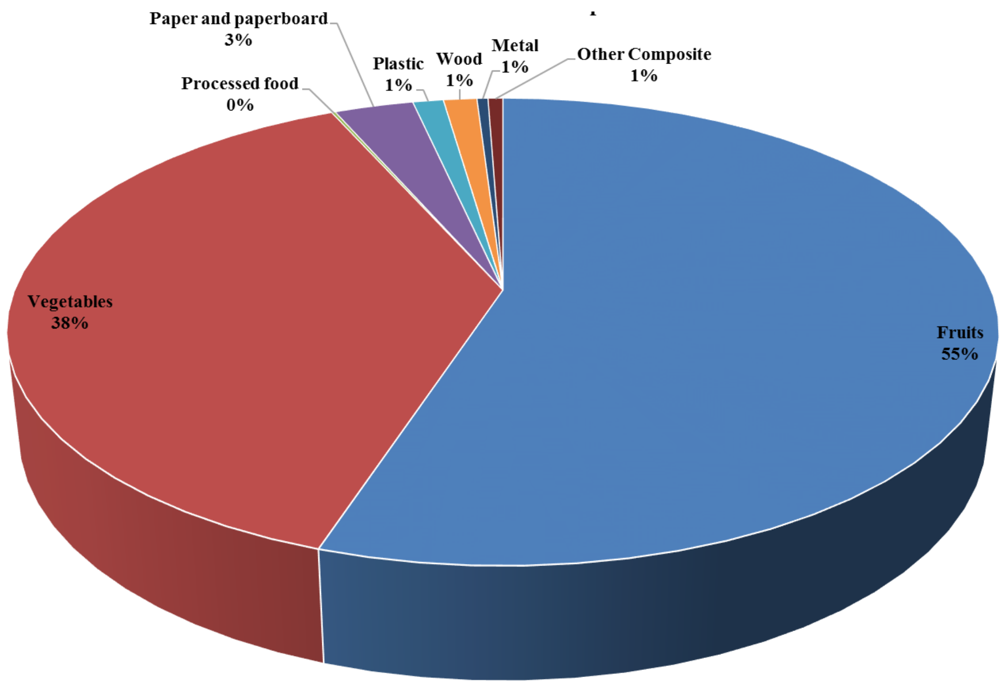


Figure 4-18 Composition of JM fruit and vegetable waste

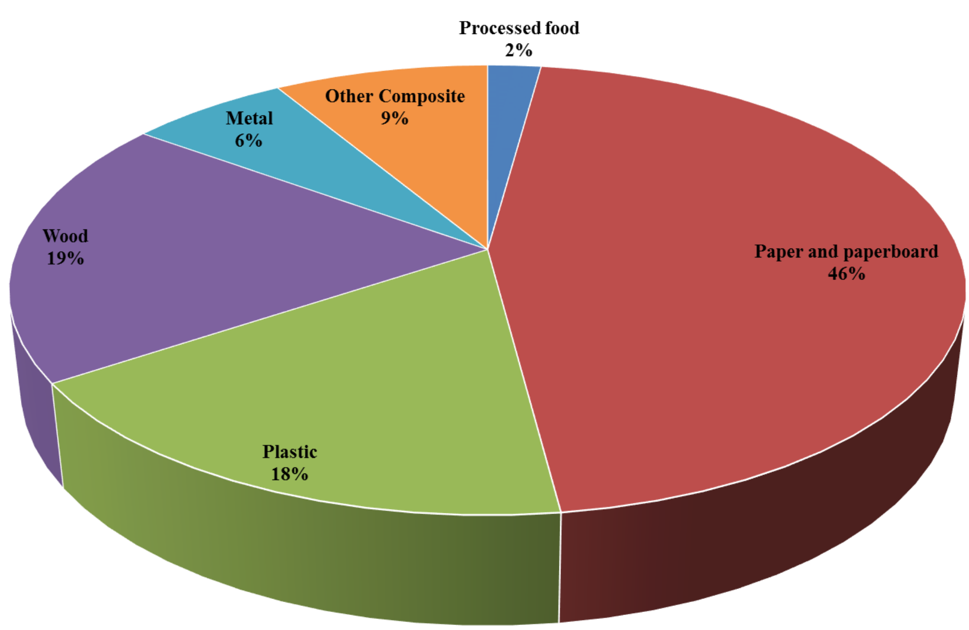


Figure 4-19 Percentage distribution of waste streams aside fruit and vegetable

It was observed that all the wastes generated at the JM ended up at Robinson Deep Landfill site. Destruction of large consignment of fruit and vegetable waste as shown in Figure 4-20 does not occurs ocassionaly. This may alter slightly the composition presented in Figure 4-18. But generally over 90% of the waste are organic and the energy recovery of this waste can be implemented.

Figure 4-20 Truck load of condemned potatoes

4.5 Inference

In the course of the entire waste composition study, it was observed that low income areas generate the largest quantities of organic wastes while the middle income and high income areas generate more of plastic wastes, papers, bottles, cans, tins, newspaper etc. The RCR waste source consist of 34% organic waste, Dailies is made up of 14% organics while 93% of JM waste is organic. All the organic wastes end up at Robinson Deep landfill site. Emissions associated with transportation of wastes to a central site for landfilling and methane emission due to decomposition can be greatly reduced with the implementation of anaerobic digestion for energy recovery. These organic wastes also impact human health and the environment negatively since through it greenhouse gases are being emitted into the atmosphere and this contributes to global warming.

During the two weeks' exercise, a total of 5.5 ton of waste was directly weighed by the UJ team as presented in Table 4-1.

Table 4-1 Weight of waste directly weighed by UJ team

Waste Source	Weight weighed (kg)	Organic Weight (kg)
RCR	1400	476
Dailies	1000	140
JM	3100	2883

4.6 Estimated Mass of Waste Sources Delivered to Robinson Deep

During the waste quantification exercise, weighing bridge at Robinson Deep Landfill wasn't functional. Hence the daily mass of waste discarded at Robinson Deep could not be accurately established for RCR and Dailies. The mass of waste lifted from JM was based on estimate and interviews on the number of skips and the frequency which the roller skip was loaded with waste and discarded at Robinson Deep. Hence all data presented below are rough estimates based on historical data extracted for six years from the Pikitup annual report. Table 4-2,Table 4-3,Table 4-4, and Table 4-5 summarises the extracted historical data for the four landfills, fractional composition of waste stream, annual tonnages and daily tonnages respectively.

Table 4-2 Tonnages of waste discharged at landfill sites in CoJ

Year/Landfills	Robinson Deep	Marie Louise	Goudkoppies	Ennerdale	Ton/ann
2008-09	363,661	383,265	221,911	130,602	1,099,439
2009-10	521,417	334,616	295,716	114,363	1,266,112
2010-11	449,254	417,578	470,278	121,710	1,458,820
2011-12	594,261	512,798	428,669	127,108	1,662,836
2012-13	670,166	472,738	420,415	106,698	1,670,017
2013-14	773,409	320,688	326,016	91,296	1,511,409
Average (ton/annum)	**562,028**	**406,947**	**360,501**	**115,296**	**1,444,772**
Average (ton/day)	**1,539.80**	**1,114.92**	**987.67**	**315.88**	**3,958.28**

Table 4-3 Percentage of total weight for waste source of interest

% of Total (Waste source of interest)	RCR	Dailies	Garden
2013/2014	54.04%	1.50%	11.05%
2012/2013	59.29%	1.58%	10.78%
2010/2011	46.00%		
	53.11%	**1.54%**	**10.92%**

Table 4-4 Annual tonnages of waste sources of interest for the four land fills

Annual (ton/year)	Robinson Deep	Marie Louise	Goudkoppies	Ennerdale
RCR	298,493.07	216,129.64	191,461.99	61,233.79
Dailies	8,655.23	6,266.99	5,551.71	1,775.56
Garden	61,345.36	44,418.28	39,348.67	12,584.58

Table 4-5 Daily tonnages for waste sources of interest

Daily (ton/day)	**Robinson Deep**	**Marie Louise**	**Goudkoppies**	**Ennerdale**
RCR	817.79	592.14	524.55	167.76
Dailies	23.71	17.17	15.21	4.86
Garden	168.07	121.69	107.80	34.48
	1,010	**731**	**648**	**207**

For JM waste, 7 skips are filled daily with waste. Also a rear end detachable truck frequently loads waste apart from the 7 skips to discharge its content at Robinson Deep Landfill site. The data presented in Table 4-6 were estimated values based on the number skips lifted from JM, the type of waste, load rate and the frequency of the rear end detachable truck. On average between 39 ton and 67 ton of waste are generated per day at JM. Based on market interview conducted, metrological variation is one factor that highly affects the amount of waste generated.

Table 4-6 Estimated tonnages of waste over the five day quantification

Days	Mon	Tue	Wed	Thur	Fri	Daily average
Mass (kg)	66,928	44,193	39,046	45,186	54,128	49,896

As at the time of compiling this report, the weighing bridge at Robinson Deep Landfill has been installed. However, it has not yet been commissioned for operations. Based on the historical data and approximated estimate, the total organic waste generated and discarded at Robinson Deep Landfill per day from RCR, Dailies and JM waste sources is 328 ton on average as presented in table Table 4-7. Data on garden waste has been included in Table 4-4 and Table 4-5 as this is also biodegradable. However, depending on the lignocellulose content of the garden waste some degree of pre-treatment might be required. Hence if considered as a substrate the total mass of organic waste available as a substrate will be 496 tons/day. This feasibility study only focuses on the three sources highlighted earlier as presented in Table 4-7.

Table 4-7 Mass of organic waste generated per day from the three sources

Robinson Deep	**Ton/day**	**Organic fraction**	**Ton of organic/day**
RCR	817.79	0.34	277.88
Dailies	23.71	0.14	3.43
JM	49.90	0.93	46.40
	891.40		**327.71**

4.7 Energetic potential of organic waste

If all wastes are fed as substrate into an anaerobic digester, the annual biogas potential is calculated to be 14,096,057 m^3 with energy potential of 291,274 GJ as presented in Table 4-8. Other energetic equivalent of biogas produced from the OFMSW to Robinson Deep Landfill is presented in Table 4-9. The theoretical annual CO_2 reduction from diverting this waste is 124,327 tCO_{2eq}.

Table 4-8 Energy potential of all organic waste quantified

Energy potential of all organic waste	Organic material	Quantity organic (tons/yr)	Biogas (m3/yr)	Energy (GJ/yr)	Energy production
RCR	56%	101,426	7,099,820	140,167	48%
Dailies	1%	1,252	97,489	2,106	1%
Fruit and Vegetable	9%	16,936	1,318,806	28,486	10%
Garden waste	34%	61,345	5,579,941	120,516	41%
		180,959	**14,096,057**	**291,274**	

*Table 4-9 Equivalent of other fuel to biogas and CO_2 reduction**

Other fuel	Equivalent
Natural gas (m^3/yr)	8,457,634
Diesel (l/yr)	8,006,842
Petrol (l/yr)	9,024,296
Electricity (MW)	3.06
CO_2 equivalent reduction (tCO_{2eq}/yr)	124,327.22

**Assuming biogas with 60% methane and 35% conversion efficeincy from methane to electricity*

**1 Nm^3 of biomethane equals 0.9467 l of diesel and 1.067 l of petrol*

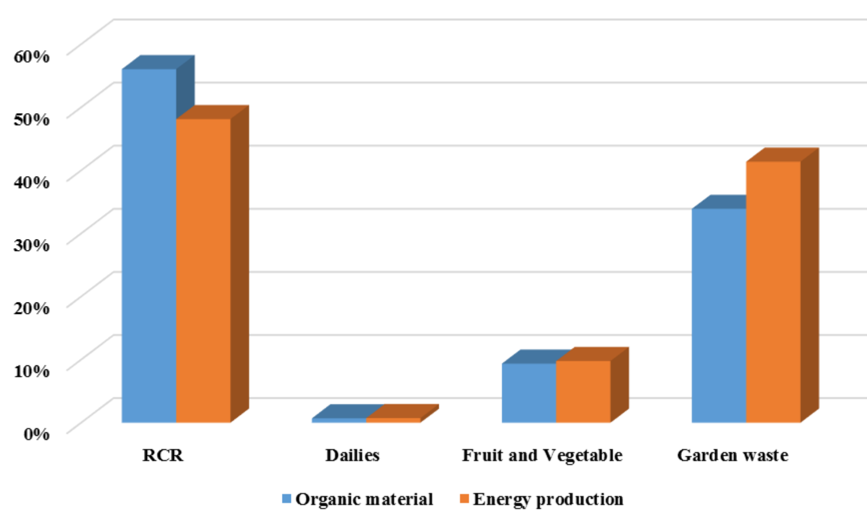


Figure 4-21 Comparison of quantity of organic material and their energy potential

Figure 4-21 shows that garden waste and JM fruit and vegetable waste yields a higher energy per unit mass than the RCR. Despite the low energy content of RCR per unit mass, it is the most readily available waste by mass but requires a high degree of separation unlike JM fruit and vegetable waste which require less sorting.

4.8 Waste Characterisation

The physical composition of the MSW is important in the design, selection and operation of equipment for the biogas plant. Waste composition, moisture content, waste particle size, density, temperature and pH are salient variables as they affect the extent and rate of degradation of waste. The chemical composition of MSW is important in evaluating alternative processing and energy recovery options. Typically, MSW can be thought of as a combination of semi-moist combustible and non-combustible materials.

4.8.1 Methodology

Important properties usually analysed when MSW is to be used as fuel are;

a) Proximate Analysis

- Moisture Content (loss at 105 °C for 1 hour): Moisture content (MC) is very important during anaerobic digestion, as it determines the amount of total solid to be fed into the digester. In order for a feedstock to be suitable for anaerobic digestion, its percentage MC should be between 68-80%. Generally, feedstock with high MC (from 80% upwards) is not economically feasible as feedstock due to low methane production per wet weight. Moreover, feedstock with TS less than 10% requires large digester volume. Food waste, fruit and vegetable waste in particular, normally contain high MC, which indicates low TS.
- Total solid: Total solids are all organic and inorganic compounds present in the feedstock. TS are basically used to classify the anaerobic digestion process. Anaerobic digestion system with less than 10% TS, are generally referred to as low solids (LS) anaerobic digestion systems. Medium solids (MS) contains about (15-20% TS) and high solids (HS) contains 22-40%. As %TS of feedstock increases, the volume of digester decreases.
- Volatile matter: Volatile solids content are the main constituent that can drastically affect the methane production during anaerobic digestion of agricultural waste. The biodegradability of a substrate is measured by biogas yield or methane yield and percentage of solids (total solids or volatile solids). In actual sense, biogas or methane yield is measured by the amount of biogas or methane that can be generated per unit of volatile solids content contained in a substrate. Therefore, higher VS ratio will have greater biogas or methane production. Fruit and vegetable

wastes tend to have low total solids and high volatile solids, and are easily degraded in an anaerobic digester. The fast hydrolysis of these fruit and veggies may lead to acidification of a digester and the subsequent inhibition of the process. Hence co-digestion is mostly preferred

- Ash: Ash is the residue after burning.

b) Ultimate Analysis (percent carbon, hydrogen, oxygen, nitrogen, sulphur and ash)

The result of ultimate analysis is used to characterise the chemical composition of the organic matter in MSW. They are also used to define the proper mix of waste materials to achieve suitable C/N ratios for biological conversion processes. A balanced ratio between macronutrients and micronutrients is needed to ensure stable management of the process. After carbon, nitrogen is the nutrient most required. It is needed for the formation of enzymes that performs metabolism. C/N ratio has been considered as the main factor that determines the efficiency of the production. C/N ratio replicates the amount of nutrients available in the feedstock and therefore the performance and the stability of the process is sensitive to C/N ratio. Optimum C/N ratios for enhanced biogas production are between 10-30:1. A higher C/N ratio (more of carbon and not much of nitrogen), inadequate metabolism may mean that carbon present in substrate is not completely converted and results in low biogas production. Low C/N (much of nitrogen and less carbon) leads to ammonia accumulation and high pH value exceeding the optimal pH for methanogens. Although, ammonia may be used for buffering or pH balancing, the concentration needs to be controlled because even in low concentration, it will inhibit the growth of the bacteria and in worse case can lead to collapse of the entire microorganism. The C/N ratio may be balanced by mixing two or three substrates with different characteristics under a process, referred as co-digestion. Aside nitrogen, sulphur and phosphorus are also essential. For overall system optimality, the C:N:P:S ratio of substrate in the digester should be 600:15:5:3.

4.8.2 Procedure for Proximate and Ultimate Analysis

The physical characteristics of the substrates were measured using standard protocol. The procedure is given below

a) Preparation

- Crucible waste heated to 550 °C for 1 hr
- The crucible was placed in a desiccator for cooling

b) TS Determination

- Crucible was weighed and value recorded
- 100 g of representative sample was added to the crucible

- The crucible with the sample was placed into a preheated oven to 105 °C and the volatiles allowed to evaporate for 20 hrs. TS is calculated as the ratio between the amount of dried sample and the initial amount of wet sample as given in equation 1.

c) VS determination

- Crucible was taken out of oven and allowed to cool to room temperature in a desiccator
- Crucible was weighed and value recorded
- Crucible was transferred into a furnace pre-heated to 550 C (ignition)
- After 2 hrs, dish is taken out of furnace and allowed to cool to room temperature in a desiccator
- Crucible was weighed and value recorded. VS content can be expressed as a percentage of TS or as percent of wet sample. Equation 2 is VS expressed as percentage of wet weight

$$TS\% = \left(\frac{m_{dry}}{m_{wet}}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \, eq\ 1$$

$$VS\% = \left(\frac{m_{dry} - m_{ash}}{m_{dry}}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. \, eq2$$

$$MC\% = \left(\frac{m_{wet} - m_{dry}}{m_{wet}}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots ... \, eq\ \mathbf{3}$$

Where: m_{wet} is mass of wet waste; m_{dry} is mass of waste after 1 hr at 105 °C, m_{ash} is mass of waste after further heating at 550 °C for 2 hrs.

shows the process carried out to determine the physical characteristics of the substrates

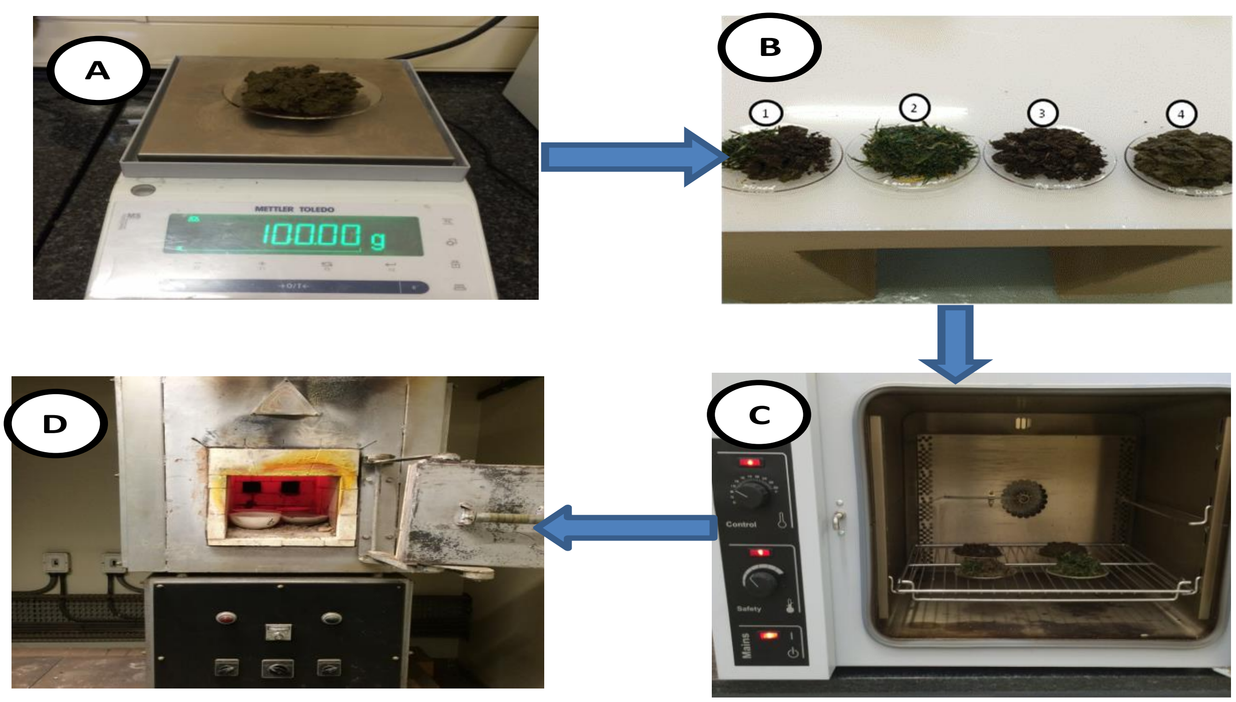


Figure 4-22 Equipment used for Proximate analysis with flow lines illustrating the sequence of operation

A= Analytical Balance used to weigh the samples; B = Weighed out samples ready for the oven; C= Pre-heat Electric Hot Air Oven with the samples inside; and D = Furnace used to determine Ash Content

4.8.3 Results

The proximate analysis result for all waste streams have been presented graphically.

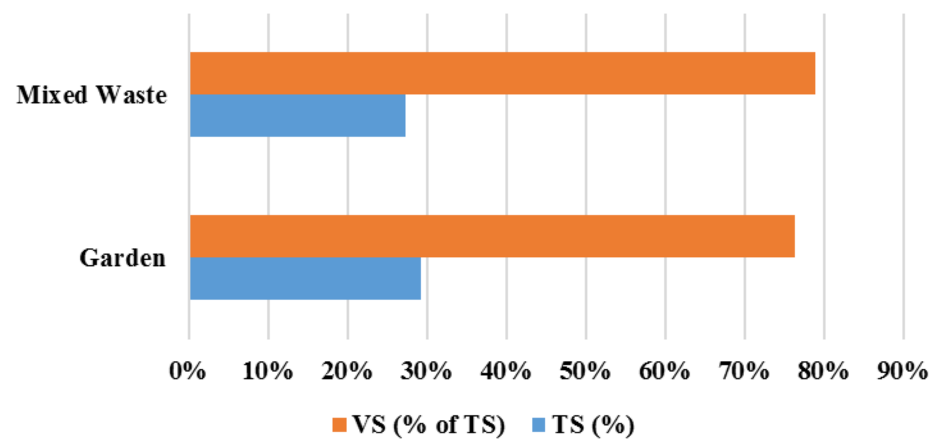


Figure 4-23 Proximate analysis of mixed RCR, dailies and garden waste

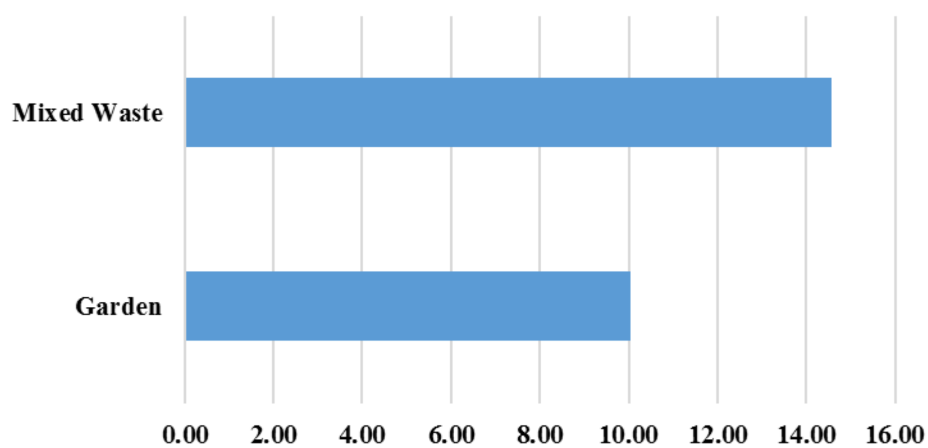


Figure 4-24 C/N Ratio of Robinson Deep RCR, Dallies and garden waste

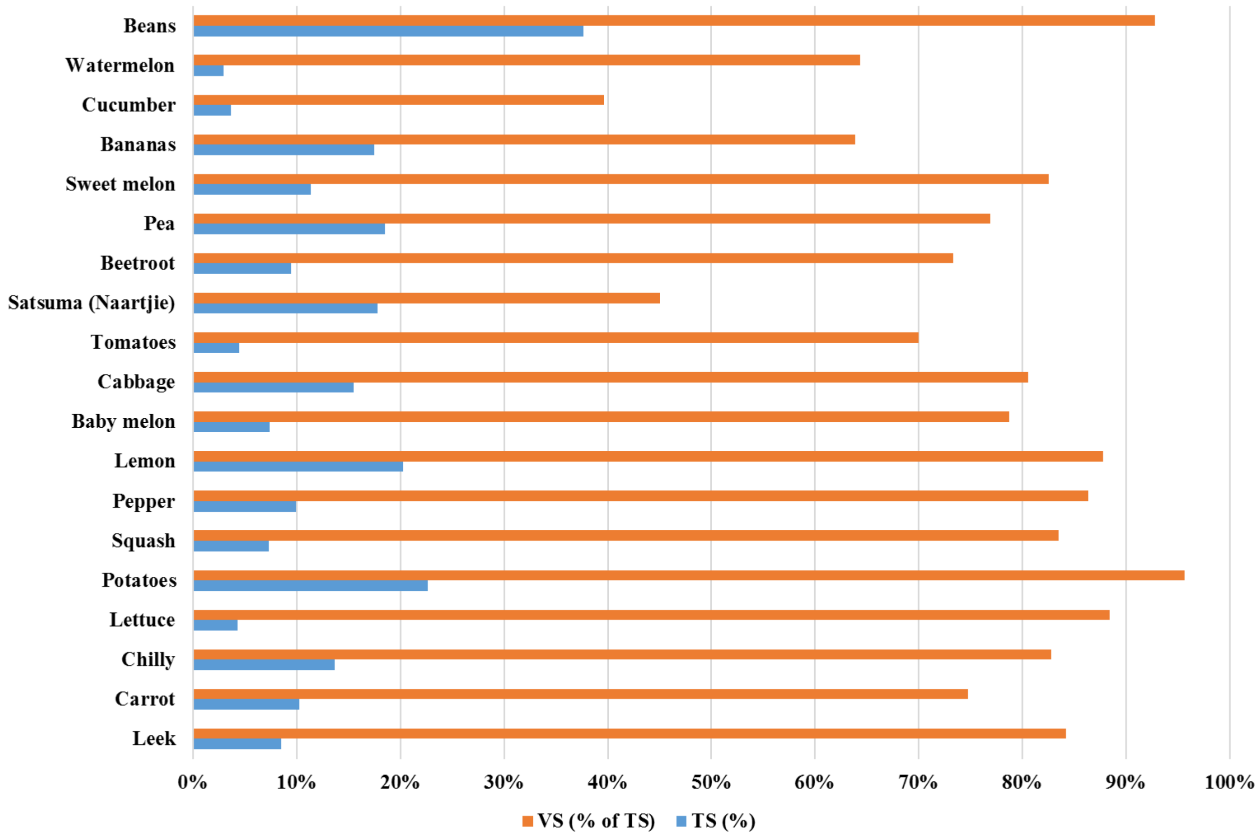


Figure 4-25 Proximate analysis of JM fruit and vegetable waste

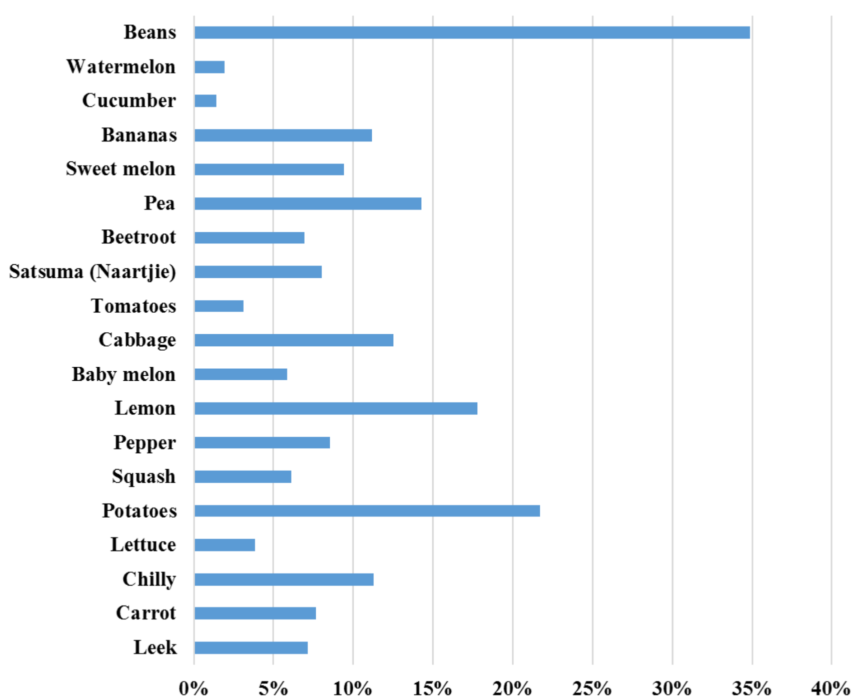


Figure 4-26 VS as a percentage of wet weight

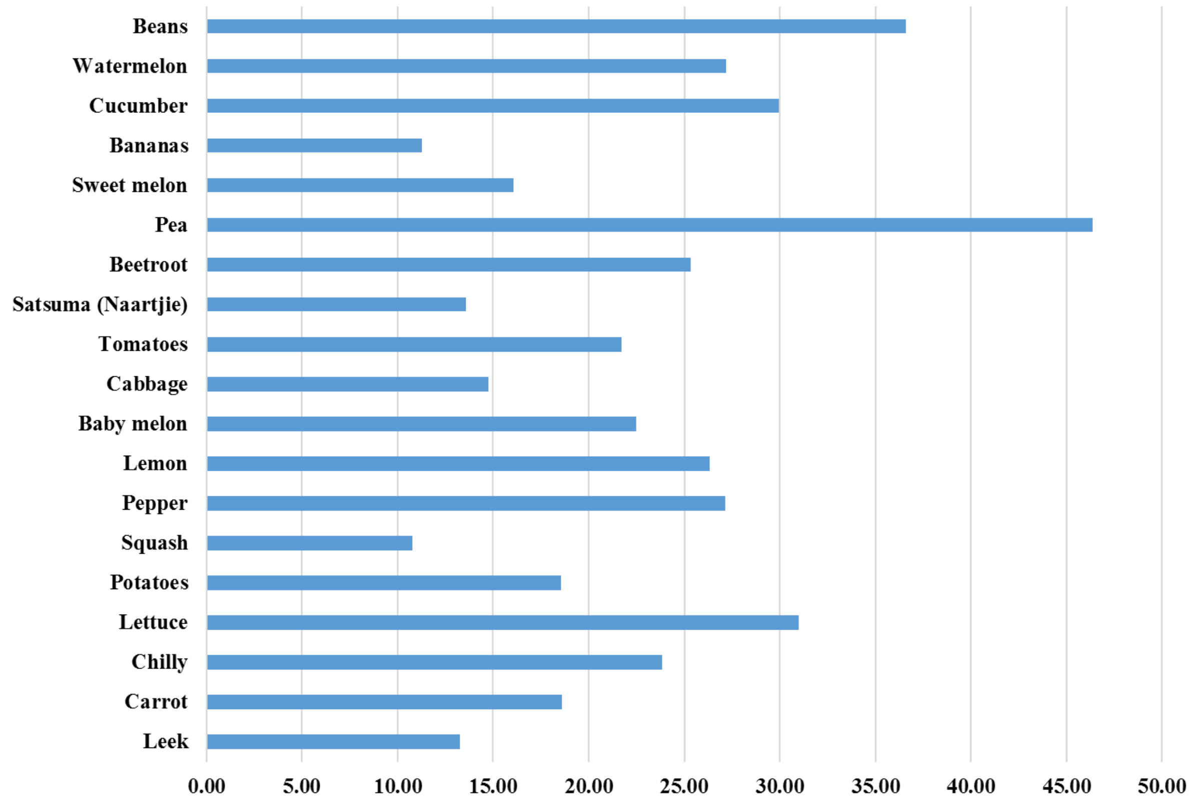


Figure 4-27 C/N ratio of JM fruit and vegetable waste

4.8.4 Inference

From Robinson Deep's substrates, it was observed that there was no significant difference in TS% between mixed waste and garden waste. TS% for mixed and garden waste was 27.33 and 29.26%, with moisture content of 72.67 and 70.74 respectively. The high TS of mixed MSW is due to the heterogeneous nature of the waste with elements of uncooked grains, some garden waste and other foreign bodies. VS (TS %) was relatively high, favouring anaerobic digestion, and ranged between 76.32-78.96%. The C/N ratio for both substrates was within the optimal range (10-30:1), indicating balanced nutrients (C/N) required by micro-organisms during AD. Mixed waste had C/N ratio of 14.56 while garden had 10.1.

The substrates from JM as expected, had higher moisture content. The VS expressed as a percentage of TS is also high. The VS (%TS) ranges from 40% for cucumber to 96% for potatoes. The average VS (%TS) for the sampled fruit and vegetable is 78% with a median of 82%. About 99% of substrates from JM had C/N ratio within the optimal ratio (10-30), with few (1% of substrates) being above the optimal. The highest C/N ratio of about 36.59 and 46.36% was observed in beans and pea respectively, indicating the lake of nitrogen from the substrates. From samples with high C/N ratio, co-digestion with substrate of low C/N ratio are recommended.

From the ultimate and proximate analysis of the waste stream characterised, mono-digestion is possible as both sources are within acceptable range of parameters studied. However, for optimality and to reduce the need for high level control of process parameters, co-digestion of waste streams are recommended.

5 Biochemical Methane Potential Analysis

To evaluate the anaerobic biodegradability of an organic substrate and predict its potential to produce methane via anaerobic digestion, a test known as biochemical methane potential (BMP) is used worldwide. Understanding the potential of a substrate to produce methane and its dynamic degradation profile have a significant impact on the choice of organic substrate to digestate when producing biogas, as well as providing a better understanding of the quality of the biogas produced from a generating facility. The latter has in turn an impact on the total volume of upgraded biogas to biomethane that can be produced from commercial plant. Thus, understanding the methane potential of a substrate can have a direct bearing on the profitability of the plant for the producer, as well as the volume of biomethane that can produced.

5.1 Methodology

The methanogenic test procedure normally involves inoculating a number of vials containing a small amount of the target media with anaerobic inoculum, incubating them at a controlled temperature and periodically checking for the methane produced and analysing the gas composition using a gas chromatography. This method is prone to error aside been very expensive. For the BMP analysis in this report, an automatic methane potential test system (AMPTS II) have been deployed for on-line measurements of ultra-low biogas and biomethane flows produced from anaerobic digestion of any biological degradable substrate (both solid and liquid form). The system is integrated into a gas chromatography equipment. The apparatus and materials that were used for the study comprise the following:

- Bioprocess Control AMPTS II machine
- SRI Gas Chromatography for analysing the gas composition
- pH meter to measure the pH of the initial feedstock before AD
- Scale for weighing the substrate and inoculum
- The OFSMW from Robinson Deep landfill and fruit and vegetable waste from JM
- Cow dung to provide the necessary bacteria for the digestion process
- The following chemicals were used to adjust the pH since they were mostly acidic to a range of 6.5-7.5, Sodium Hydroxide (NaOH), calcium hydroxide $Ca(OH)_2$, calcium carbonate $CaCO_3$ and vinegar to lower for those that were alkaline.
- Deionized water (H_2O) was used to prepare the solutions and also for the equipment (water bath and flow cell).
- Nitrogen (N_2) gas is used to purge the entire system, allowing for an anaerobic environment.

- T-union fitted with septa for sampling
- A syringe for sampling

5.1.1 Procedure

Bioprocess control AMPTS II was used to perform BMP for OFSMW and FVW. The AMPTS II consist of a digester, CO_2 fixing unit and gas collection unit. The setup is batch process. A 500 mL digester, with effective volume of 400 mL, was used for biogas production which had head space of 100 ml. Sodium hydroxide (NaOH), obtained from Sigma-Aldrich, South Africa, was used for CO_2 removal. A 3M NaOH solution was prepared by mixing 240 g pure NaOH with distilled water up to 2 l. The solution was used as the scrubbing solution to absorb the impurities. A pH indicator solution was added to NaOH solution with 0.4% thymolphthalein pH-indicator solution (40 mg in 9 ml ethanol 99.5% and 1 ml water). The prepared NaOH awith pH indicator was used to determine the saturation point for the cleaning solution to be replaced. The substrate was prepared and fed into the digester. The digester was purged with nitrogen to remove the oxygen and create an anaerobic condition. The digester was connected to a 100 ml bottle containing 80 ml NaOH & pH indicator solution, which was used as scrubber. The gas exiting the CO_2 fixing unit was sent to the flow cell (gas collection) where the volume of biomethane is determined using the buoyancy principle. The experimental setup is as presented in Figure 5-1.

Figure 5-1 AMPTS II experimental setup for BMP analysis

5.2 Results

Figure 5-2 and Figure 5-3 show BMP of mixed substrate using different alkaline solution to control the pH of the process. Calcium trioxocarbonate ($CaCO_3$) shows a very high yield of biogas with CH_4 concentration of 51.14%. However due to the negative impact of $CaCO_3$ on growth of plant as it has been reported to reduce water permeation into the soil hence retarding growth of plants, the use of CaCO3 was discontinued.

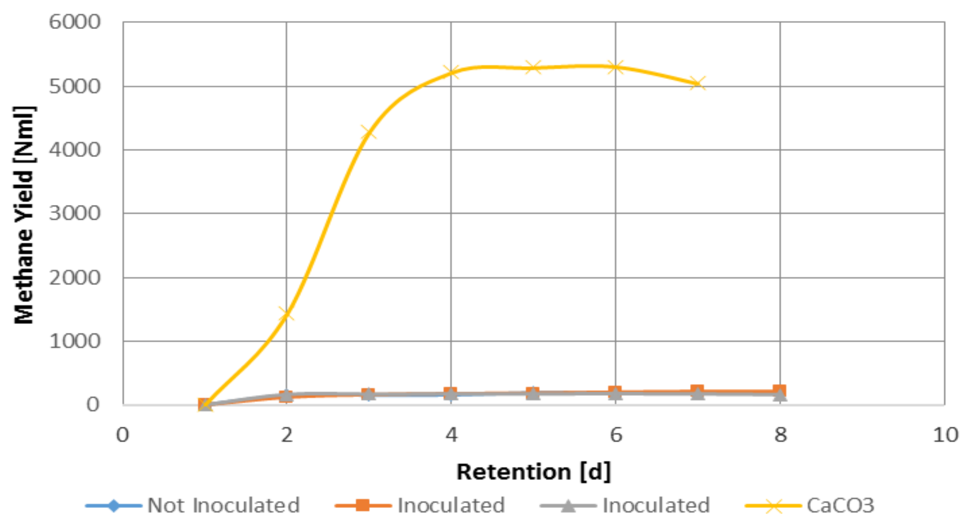


Figure 5-2 BMP result with $CaCO_3$ as a pH control

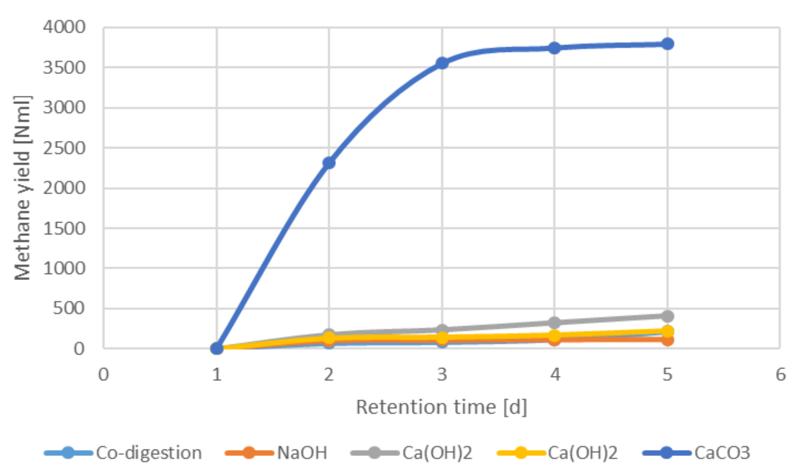


Figure 5-3 BMP result investigating different alkali solution for pH control

During the first series of runs of the BMP analysis and maintaining ratio of waste as presented during quantification, inhibition of the process was observed after three days and four days at most. BMP was on average of 0.13 ml CH_4/gVS. Consultation onto the cause of such inhibition, it was observed having higher fruits than vegetables during digestion increases the acidification forming rate of the process.

Also consultation with the AMPTS II manufacturer, the team was advice to double the inoculum to substrate ratio and observe the performance of the system. Figure 5-4 shows improved performance for mixed and a more consistent result without any alkaline solution to pH balance. Figure 5-5 shows average BMP with standard deviation bar.

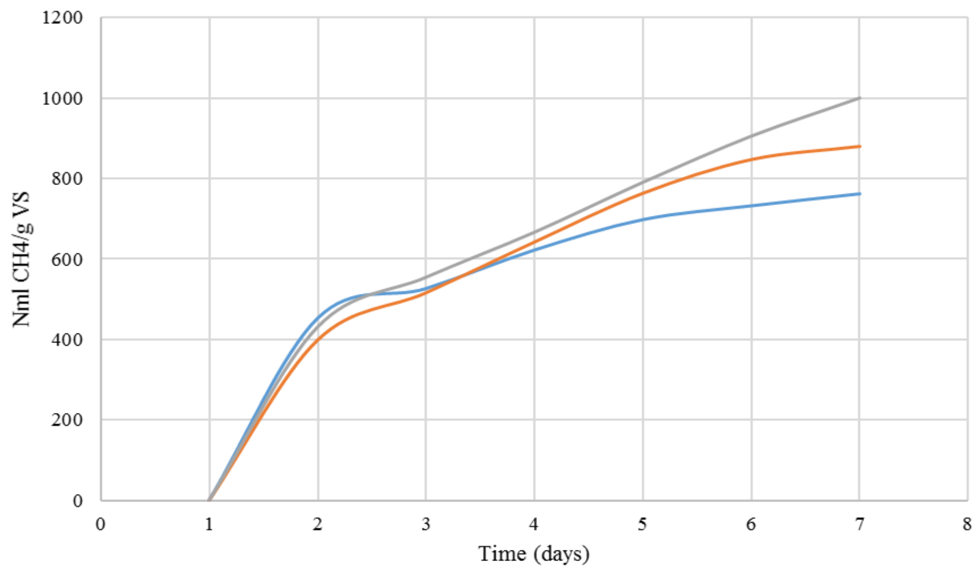


Figure 5-4 BMP Result after improved feed conditions

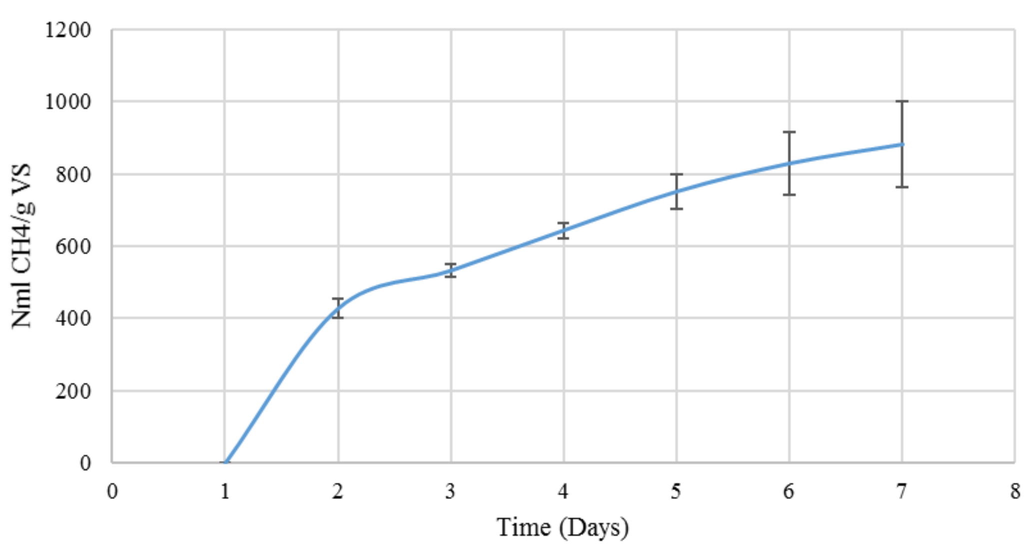


Figure 5-5 Average BMP with standard deviation bar

5.3 Inference

Improved feed condition and inoculum to substrate ratio (ISR) have great impact on the biogas yield. Initial result indicated a BMP of 310 m^3 CH_4/kgVS with average CH_4 concentration of 59.46 %. The GC graph is presented in Appendix. This gives a 510 m^3 biogas/kgVS. Results presented in Figure 5-4 and Figure 5-5 are still being conducted in the lab. Different ISR, and different composition of the substrate will be investigated to determine the optimal feed composition as well as the ISR. An experiment of this nature will involve multiple repeated trials alongside incorporating seasonal variation of waste stream. Hence, an extended analysis is recommended.

The characterization and initial BMP result shows the potentiality of generating biogas from organic fraction of waste. BMP which is a vital aspect of predicting the potential of the waste requires an extended time incorporating different feed substrate and ISR. Due to time constraint, all needed experiment have not been covered as at the time of submitting this report. However, since this experiment is ongoing, an updated BMP result will be presented on a later date.

6 Anaerobic Digestion

6.1 Biochemical Process of Anaerobic Digestion

Biogas systems are composed of a digester to convert the waste into biogas via a multi-step anaerobic degradation process and biogas conversion system, cleaning and/or upgrading, which converts it into useful energy.

6.1.1 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 degradation process is based on parallel and cross linked reactions and proceeds through four successive stages namely; hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The degradation process is summarized in Figure 6-1.

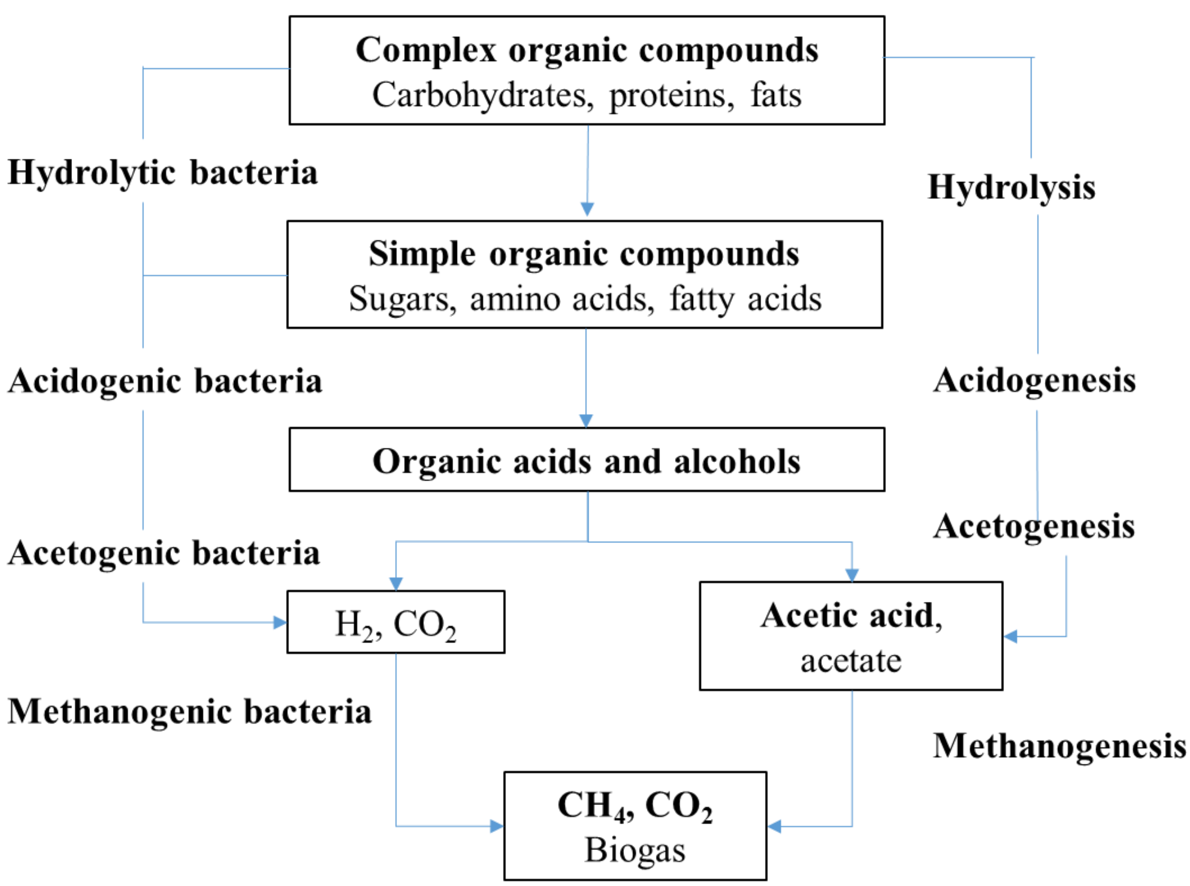


Figure 6-1 Degradation steps of anaerobic digestion process

6.2 Process Parameters

There are various parameters that control the efficiency of anaerobic digestion. These parameters provide appropriate environment for growing of anaerobic micro-organisms. They include: constant temperature, nutrient supply, nutrient supply (Carbon Nitrogen ratio), stirring intensity, nature of substrate, partial pressure, exclusion of oxygen, optimum trace element concentration, moreover presence and amount of inhibitors (e.g. ammonia). The presence of oxygen into digestion process must strictly be avoided since methane bacteria are anaerobes.

6.2.1 Temperature

The optimum temperature, i.e. the temperature at which the organisms grow fastest and works most efficiently varies among species. Microorganisms can be divided into different groups depending on the temperature at which they can best thrive and grow: psychrophilic, mesophilic and thermophilic. The optimum temperature for a specific organism is strongly linked to the environment from which it originates. The two convectional operational temperature levels for anaerobic digesters determine the species of methanogens in the digesters.

Psychrophilic occur at a low optimum temperature of around 10 °C, whereas mesophilic is around 20-45°C and thermophilic with an optimum temperature above 50°C as shown in the Fig. 6.3. At low temperatures of less than 10°C, the anaerobic process is slow, taking 3 times more than the normal mesophilic time process [27]. In experimental work at University of Alaska Fairbanks, a 1000L digester using psychrophilic temperatures produced 200-300L of methane per day, about 20 to 30% of the output from digesters in warmer climates. Though thermophilic digestion systems are considered to be less stable and the energy input is much higher, more biogas is removed from the organic matter in an equal amount of time. The increase in temperature facilitates faster reactions and hence faster gas yields.

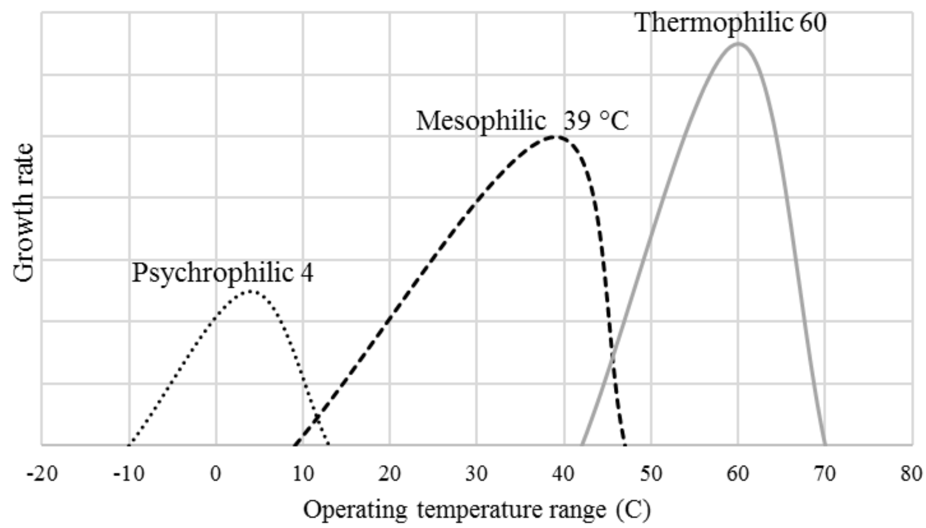


Figure 6-2 Growth of microorganisms at different temperatures

6.2.2 pH

pH is the measure of H+ ions in a solution, otherwise known as a method of determining whether a solution is an acid or a base. The pH scale ranges from 0-14, with 7 being neutral, less than 7 being acidic and greater than 7 indicating a base solution. In anaerobic digestion, it is crucial to measure the pH throughout the entire process to ensure the health of the methanogens. As with living beings, methanogens require a particular environment so that it may live and prosper. They require an environment between the pH ranges of 7 to 7.5. It was reported that there are several biogas processes in Sweden currently operating at pH values of 8. In the acidogenesis process, acid is produced which thus lowers the pH of the digestion tank. It is therefore important to constantly measure the pH to ensure continued wellbeing of methanogens and thus methane production. However, methane production does not usually occur because the pH is too low, instead it starts in the digestion tank where the pH is higher.

6.2.3 Retention time

Retention time is defined as the time it takes to replace all the material in the digestion tank. It varies with the amount and type of feed material, the configuration of the digestion system and whether it be one stage or two stage process. The length of the retention time needed depends partly on the composition of the substrate and the digestion temperature. Microorganisms generally manage to decompose a substrate rich in sugar and starch, which is easily broken down, in a short time. An example is industrial waste water that only contains soluble organic matter. In this case, no hydrolysis is necessary, which allows for a relatively short retention time (RT).

On the other hand, microorganisms may need significantly more time to effectively attack and break down fibre-rich and cellulose-rich plant matter. For such material, it is often hydrolysis and not methanogenesis that limits the rate of decomposition. In Germany, among other places, retention times of up to 50-100 days are used to ensure stable operation and satisfactory digestion of energy crops. In the case of a single stage thermophilic digestion, residence times may be in the region of 14 days, which compared to mesophilic digestion is relatively fast. In a two stage mesophilic digestion, residence time may vary between 15 to 40 days.

Retention time is usually referred to as hydraulic retention time (HRT), and for the biogas process it is usually between about 10 and 25 days, but can also be longer. Sometimes the retention time of the particulate material, or solids retention time (SRT), in the process is listed instead. In many cases, HRT and SRT are equal, but in a digestion tank in which part of the residues are returned to the process, SRT becomes longer than HRT. This may occur, for example, during digestion of industrial sewage sludge, where added material has high water content and where the recirculation of digested, thickened sludge, including biomass, allows a longer time for the microorganisms to break down the incoming organic matter. In countries with colder climates; the HRT may go up to 100 days as compared to warmer climates where the values lie between 30-50 days. Shorter retention time is likely to face the risk of washout of bacterial population while longer retention time requires large volume of the digester and hence more capital.

6.2.3.1 Hydraulic Retention Time (HRT)

The HRT is the average time interval the substrate takes inside the digestion chamber. It is correlated to the inner-volume of digestion chamber and the volume of substrate fed per time unit, according to equation 1.3:

$$HRT = \frac{\boldsymbol{VDC}}{\boldsymbol{DMU}} \qquad (1.3).$$

Where:

HRT = Hydraulic Retention Time (day)

VDC = Inner-Volume of Digestion Chamber (m^3)

DMU = Discharge of pumping and Mixing Unit (m^3 / day).

The characteristics of substrate determines the retention time of substrate in the digester. Generally, although most wet AD plants operate in a continuous basis, the aim is for the material to remain within the digester from 20 to 40 days. Longer retention times are possible, but require greater tank capacity for upholds but with time the biogas output reduces. For greater proportion of solid material such as cellulose crops, retention time needs to be increased to achieve optimum biogas output and material throughout.

6.2.3.2 Solid Retention Time (SRT)

The SRT control the conversion of solids to gas. It is also important factor in maintaining digester stability in AD process. The calculation of solids retention time is the quantity of solids maintained in the digester divided by the quantity of solids wasted each day. It can be calculated according to the equation 1.4:

$$\mathrm{SRT} = \frac{\mathbf{VDC} * \mathbf{TSC}}{\mathbf{QWD} * \mathbf{TSW}} \qquad (1.4).$$

Where:

SRT = Solids Retention Time (day)

VDC = Inner-Volume of Digestion Chamber (m^3)

TSC = Total Solids Concentration in the digester (kg / m^3)

QDW = Daily Quantity of Waste (m^3 / day)

TSW = Total Solids concentration of the Waste (kg / m^3).

6.2.4 Degree of digestion

The degree of digestion is defined as the percentage of the organic material broken down and converted into biogas during a specific period of time. Generally, batch processes have a higher degree of digestion than continuous digestion. In a batch process, the degree of digestion can theoretically be greater than 90%. However, it is normally not economically or practically possible to extract all the methane from a given substrate.

In batch digestion, biogas production is normally greatest at the start of the process. Later, less biogas is formed over time. The degree of digestion also varies with the substrate. Readily biodegradable substrates, such as the liquid from pressed sugar beets, can have a degree of digestion of more than 90%, while only a little more than 60% of a high-fibre grass crop is degraded during the corresponding period. Generally, the lower the degree of digestion in the actual digestion tank, the greater is the potential for methane production in this post-storage stage. It is always important that this subsequent digestion takes place in covered containers to prevent the methane gas and other environmentally harmful gases from leaking into the atmosphere

6.2.5 Loading rate

Loading is a term that indicates how much new material is added to the process per unit of time. It is usually referred to as organic loading rate (OLR). In this case it is important to know the dry solids (DS) and volatile solids (VS) content in the substrate in order to give the biogas process the right loading rate. Dry solids are the material that remains when all of the water is dried off, while VS indicates the organic part of the dry solids. Studies have shown that methane yield increased with a reduction in the loading rate. If the loading rate is too high, there will be more substrate than the bacteria can decompose. If a large amount of substrate is suddenly added at the start of a process, there are simply too few microorganisms to be able to absorb this quantity of food. An excess of under composed material, such as different fatty acids, builds up. This, in turn, results in a reduction in pH and the creation of an imbalance in the entire decomposition chain. The process is no longer stable.

6.2.6 Digestion Chamber Loading

Digestion chamber loading refers to the amount of feedstock feeding into the digestion chamber per day per m^3 of digestion chamber volume. Increasing the digestion chamber loading will reduce the digestion chamber volume and also reduce the percentage of volatile solids converted to gas. In general better digestion can be achieved at lower loadings. Mesophilic reactors appear to achieve greater conversions at lower loadings while thermophilic reactors appear to achieve greater conversions at high loadings. In typical anaerobic digester, the digestion chamber loading approximately from 1 to 5 kg / m^3.day.

The digestion chamber loading can be calculated if the HRT and influent waste concentration is known according to equation 1.5:

$$LDC = \frac{\boldsymbol{CIW}}{\boldsymbol{HRT}} \qquad (1.5).$$

Where:

LDC = Digestion Chamber Loading (kg of TS or VS / m^3 of digestion chamber volume. day).

CIW = Influent Waste Concentration (kg of TS or VS / m^3 of digestion chamber volume).

HRT = Hydraulic Retention Time (day).

6.2.7 Mixing

Digestion tanks should be equipped with agitators to mix the substrate. Mixing facilitates contact between the microorganisms, the substrate and nutrients and provides a uniform temperature throughout the process. However, mixing ought not to be too strong. Gentle mixing benefits the formation of aggregates and prevents methane producers from being washed out in the liquid. Continuous mixing avoids sedimentation and utilizes the existing digestion tank volume in the best manner. Mixing also prevents material from accumulating on the bottom of the digestion tank and reduces the risk of foaming.

6.2.8 C: N ratio

Microbes need a 10-30:1 ratio of C: N with largest percentages of the carbon being readily degradable to meet this requirement. A methanogenic bacterium uses nitrogen to meet their protein requirements. The C/N ratio has been presented in section 4.8.3.

6.2.9 Particle size

According to EU regulation EC 208/2006, the proposed maximum particle size for adequate digestion is 12 mm. Several studies also show a clear correlation between particle size and methane yield, and for maximum digestion, particle size should preferably be just a few mm or less.

6.3 Anaerobic Digesters

Several anaerobic digester configuration and technologies exist. Each digester is designed to process specific waste stream. Anaerobic digestion could be wet (liquid) or dry (solid) digestion. They are both described briefly

6.3.1 Wet digestion

Wet digestion is suitable for substrate with total solid less than 15%. This makes the substrate liquid enough to be pumped. If substrate with higher TS are to be fed, a solid feeding device other than pumps are to be used however the particles sizes must be small enough for bacteria to break them down into biogas. Plug flow, complete mix, fixed film, upflow anaerobic sludge blanket (UASB) and covered lagoon are types of digesters based on wet digestion. Detail description of each is given in section 6.3.1

6.3.2 Dry digestion

Dry digestion is mostly applied to substrate with very high TS and the substrate retain it solid form when fed into the digester and are also expelled in solid form. Vertical and horizontal are types of digester based on dry digestion. Detail description of each is given in section 6.3.2.

6.4 Digesters configuration

6.4.1 Batch or Continuous Configuration

AD can be performed as a batch or a continuous process depending on the substrates being digested and the configuration of the digester. In a batch process, the substrate is added to the digester at the start of the process. The digester is then sealed for the duration of the process. In a typical scenario, biogas production will be formed with a normal distribution pattern over time. After digestion, biogas is collected and digester is partially emptied. They are not emptied completely to ensure inoculation of fresh substrate batch with bacteria from previous batch. These systems exist, but are not common.

In a continuous digestion process, organic matter is constantly added in stages to the digester on daily basis. In this case, the end products are constantly removed resulting in constant biogas production. A single or multiple digesters in sequence may be used.

6.4.2 Single stage or multistage Digestion

The simplest model for biogas production is to use a single digestion tank for the entire process, so-called one-step digestion. With one-step digestion, all stages in the microbial breakdown process, i.e. hydrolysis, fermentation, anaerobic oxidation and methane production take place at the same time and in the same place. It is common for one-step digestion to take place in total mixed processes. It is often used in treating sludge, food waste, manure, etc.

An alternative to a single-stage process is to divide the process into two parts, called two-stage (multi stage) digestion. In multi-stage digestion, the first step is to load raw material into a digestion tank where the process is focused on hydrolysis, acetogenesis and acidogenesis. The organic material is then heated to the required operational temperature (either mesophilic or thermophilic) prior to being pumped into the methanogenic digester. The division of the process often results in fast and efficient formation of biogas in the second stage, with methane concentrations of up to 85%. However, it is difficult to practically separate all the digestion processes.

6.5 Substrates

6.5.1 Substrates for biogas production

The most important initial issue when considering the application of anaerobic digestion system is the feedstock to the process. Almost any organic material can be processed via anaerobic digestion. However, if biogas production is the aim, the level of putrescibility is the key factor in its successful application. The more putrescible (digestible) the material, the higher the gas yields possible from the system.

Anaerobic digesters were originally designed for operation using sludge and manures. Sewage and manure are not the material with the most potential for AD as the biodegradable material has already had much of the energy content taken out by the animals that produced it. Therefore, many digesters operate with co-digestion of two or more types substrate as feedstock. For example, in a farm-based digester that uses dairy manure as the primary feedstock, the gas production may be significantly increased by adding a second feedstock, e.g., grass and corn (typical on-farm feedstock), or various organic byproducts, such as slaughterhouse waste, fats, oils and grease from restaurants, organic household waste, etc. (typical off-site feedstock).

6.5.2 Substrate composition

The composition of a substrate is very important for the microorganisms in the biogas process and thus also for process stability and gas production. The substrate must meet the nutritional requirements of the microorganisms, in terms of energy sources and various components needed to build new cells. The substrate also needs to include various components needed for the activity of microbial enzyme systems, such as trace elements and vitamins. In the case of decomposition of organic material in a biogas process, the ratio of carbon to nitrogen (C/N ratio) is also considered to be of great importance. Aside C/N ratio, micro and macro elements such as Sulphur, phosphorus have effect on the rate of degradation of the substrate. The moisture content will impact the type of digestion, feeding equipment and gas yield.

6.5.3 Co-digestion of substrates

The concurrent presence in the same anaerobic reactor of different organic wastes can improve the performance of the digestion process. Co-digestion often produces more gas than expected on the basis of gas production from the individual substrates. The explanation for this is that a complex material is more likely to include all the components that are important for microbial growth. A mixture can, for example, provide better availability of trace elements or a more optimal C/N ratio. In addition, substrates that are complex and not too uniform promote the growth of several types of microorganisms in the digester. The co-digestion of different organic substrates has been studied during the last 10-15 years and the results have showed a synergic effect of the combined treatment as the biodegradability of the resulting mixture was higher than the biodegradability of the single substrates when investigated separately. Further benefits of the co-digestion are higher biogas and energy production and the decrease of the amount of solid waste to be disposed due to the gasification of a higher percentage of the substrate. In order to achieve a stable digestion process with a mixture of substrates, it is desirable if the mixing takes place under controlled conditions in a substrate tank. It is important to know the composition of the material to get a suitable mix of different components and provide a constant supply of substrate to the microorganisms.

6.5.4 Pre-treatment

It is important for a substrate to be pre-treated before it is fed into the digester. Some consideration for pre-treatment are

- To kill pathogenic microorganisms, i.e. sanitation.
- To remove materials that cannot be degraded and/or that disrupt the process. This pre-treatment may involve tearing up and removing the plastic bags that are not broken down in the process or removing sand or cutlery from food waste that wear down grinders and shredders and sink to the bottom of the digester.
- To increase the organic material content
- To increase availability of organic matter through particle reduction and increasing solubility

6.5.5 Particle size reduction

There are many different pre-treatments applied to the substrate for the biogas process to increase its availability for decomposition. The most common is mechanical disruption using a mill, blender, screw, or rotating knives. Disintegration can also be achieved by thermal, chemical or biological means using steam explosion, heat treatment, the addition of acids/bases, ultrasound, electroporation, hydrolytic enzymes, etc. The method that produces the best results depends on the substrate's chemical composition and structure.

It is important to remember that pre-treatment does not necessarily increase the potential gas yield, i.e. the total amount of biogas that can be extracted from a certain material, even if the initial digestion stage is faster. However, the decomposition rate may be very important for the economic performance of a biogas plant. If digestion is faster, it means that the retention time at the plant may be decreased without risking a reduction in gas yield. Fig. 6.4 illustrates the importance of particle size on methane yield of sisal fiber.

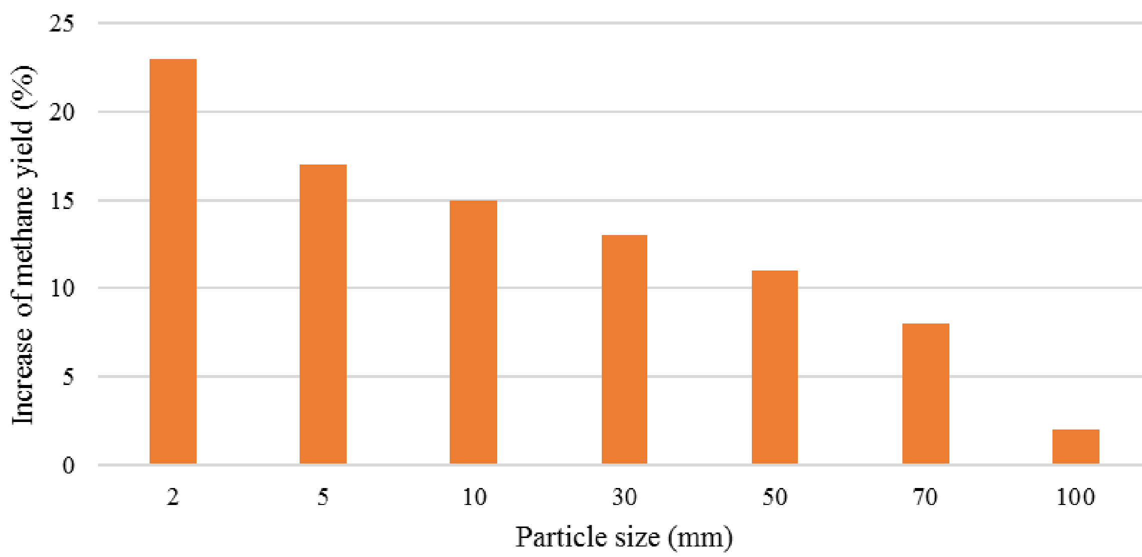


Figure 6-3 Effect of particle size on methane yield

6.5.6 Various substrates to be used

Within the scope of this study organic fraction of RCR, dailies and fruit and vegetable waste are substrate to the anaerobic digestion system under consideration. However, since this study is only focused on a small fraction of the whole organic waste, other potential sources of substrate for future consideration will be highlighted.

6.5.6.1 Stillage and other sulphate-containing substrates

Stillage (a distillation waste product from ethanol production) is not a very common substrate within the CoJ. Stillage can work well as a substrate for a biogas plant, but as the sole substrate, there is some risk that the ammonia concentration becomes too high. Only sugar is consumed during ethanol production, which is usually carried out by the addition of yeast. This makes the waste product rich in protein and the stillage can lead to processing problems due to ammonia inhibition. It is therefore very important to monitor ammonia concentrations if stillage is used as a substrate in a biogas process. The process can benefit if the stillage is co-digested with a more carbohydrate-rich material.

6.5.6.2 Municipal Solid Waste

The anaerobic digestion of OFMSW is technically feasible; however, not so many plants are utilizing it, due to the problems with the sorting of impurities. Great efforts are spent on minimizing the impurities from the MSW. For MSW substrate properties can widely vary depending on its origin of production. Climate, extent of recycling, collection frequency and cultural practices are also the factors that influence the production and composition of MSW. The cleanliness of the waste stream should be defined regarding to the purpose of AD plants. If the plant is intended to maximize the output of CH_4, mixed collection is suitable; however, if the purpose is to produce a high quality digestate, then the purity of the waste is important. Within the context of this study, RCR represent MSW. The organic fraction considered is only for the Robinson deep landfill.

6.5.6.3 Food waste

Food waste is commonly used for biogas production. The composition of food waste is usually very diverse, and because it contains proteins, fats, carbohydrates and various trace elements, it has the potential to function very well in a biogas process. However, it is important that the mixture of the waste is varied, i.e. does not contain too much meat waste in relation to vegetable and fruit wastes. If the waste contains too much protein, problems can arise with ammonia inhibition. Similarly, too much fat or sugar can cause problems as stated above.

A recent study showed that food waste, which contained a lot of fried food residues, could only be digested under stable conditions after the addition of various trace elements. Within the context of this study, Dailies collected from restaurants represent food waste.

6.5.6.4 Manure

The composition of manure from different animals varies, and therefore manure will also vary in its suitability as a substrate for biogas processes. Manure can be classified into solid and liquid manure (or slurry) depending on the dry solids content. Solid manure typically has higher carbon content and dry solids content (27%-70%) than liquid manure, since it includes straw and hay in addition to the faeces. Liquid manure is more accessible for digestion, as it contains more nitrogen and has a dry solids content of 5%-10%. Manure, especially cow dung and pig manure are often used as inoculum for the digestion process. This class of waste has not been covered in this study. A previous waste quantification study conducted by this research team indicated that Johannesburg zoo generate approximately 1.3 ton of organic waste per day with 5% been cow dung. If required, this could be added into for co-digestion.

6.5.6.5 Crop residue

Many different crops and plant materials can be used for biogas production, such as corn, grain, sugar beets, potatoes, fruit, grass, silage, etc. Many bioenergy crops also have a high C/N ratio and mixing with more nitrogen-rich material can achieve optimum process conditions. Co-digestion of energy crops with, for example, manure has been shown to generate a 16%-65% increase in methane recovery.

6.5.6.6 Slaughterhouse waste

Slaughterhouse waste contains high contents of fats and proteins, which are very energy-rich and have the potential to generate high volume of biogas. However, excessive fat and protein contents lead to increased concentrations of ammonia, and volatile fatty acids, which can lead to process breakdowns. It is therefore difficult to use slaughterhouse waste as the sole substrate, especially at thermophilic temperatures, because the proportion of ammonia in relation to ammonium can easily become too high. Slaughterhouse wastes have a high C/N ratio, but with co-digestion, the likelihood of a stable process operation is significantly improved. Co-digestion with manure, sewage sludge and food waste, which improves, among other things, the C/N ratio, have all been reported to lead to more stable processes. An alternative to co-digestion is to apply a two-step digestion process. At Robinson deep landfill, only a very small fraction (<0.1%) of waste of this class was found among dailies. It could be concluded that this class of waste is not been discharged at Robinson deep landfill during the period of this quantification.

6.5.6.7 Sewage Slurry

At present, sludge is used to produce biogas for electricity generation at the Johannesburg waste water treatment plant. This sludge contains different chemical compounds with inhibitory potential due to the presence of metals and organic pollutants. It may also have a relatively low content of organic matter (3-4%). Although a large amount of biogas is produced by anaerobic digestion of sewage sludge, some of the organic matter may remain in the residual sludge, i.e. the digestion process has a relatively low efficiency in this case. This may be due to several factors. The retention time may be too short to allow time for the microorganisms to degrade the material, or the process may be inefficient due to the presence of inhibitory substances. In addition, the organic matter in the sludge is often too complex for the microbial hydrolysing enzymes to effectively "break up" the material. Pre-treatment of sludge has been shown to have a positive effect by, for example, reducing the foaming rate. Different pre-treatments and combinations of pre-treatments have also been shown to increase gas production by making the sludge more available for digestion.

Biogas potential varies from substrate to substrate. Even the expected yield from the same class of substrate differs with process condition and inherent characteristics of the waste. Figure 6-4 gives an average biogas yield per ton.

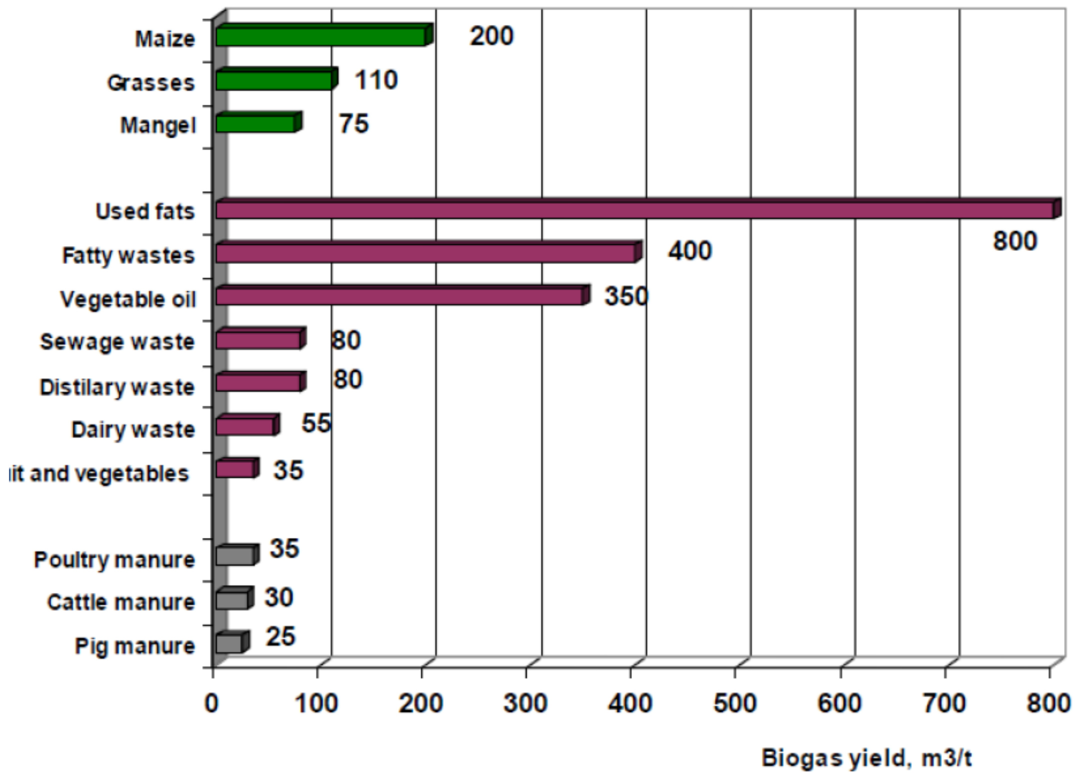


Figure 6-4 Biogas yield of various substrate

6.6 Different Technologies of Biogas Plants

There are several technical and operational alternatives to choose from the different technologies applied from small scale to large scale according to the following factors:

- Quantity of substrate available
- Investment cost
- Operational costs
- Technical know-how
- Intended end-use of products

Process requirement for small scale biogas plant are minimal in terms of equipment while for large scale waste handling and process management requires more efficient equipment. On both processes, feedstock quality requires high level of management for optimal biogas yield.

6.6.1 Different Scales of Biogas Plants

Generally, biogas plants can be classified into three different scales according to size:

- Household biogas plants
- On-site plants
- Centralized biogas plants

6.6.1.1 Household Biogas Plants

Household biogas plants are simple, small and manually operated. They effectively operate under warm climate conditions while during cold seasons, they require external temperature control device. The biogas yield from this plants is usually use in cooking and lighting in household. The digester sizes are in the range of 4-10 m^3 and produce up to 2 m^3 of biogas per day.

6.6.1.2 On-site of Biogas Plants

On-site biogas plants are integrated within the facility where the waste is been generated or discharged. They have basic automation and simple technology to maintain a stable process, while larger biogas plants use complex technologies and more advanced. They are classified into three categories. This is according to their energy production capacity.

- Small scale ≤ 70 kWh
- Medium scale 70 - 150 kWh
- Large scale 150 - 500kWh

An example of an on-sit biogas plant is the biogas plant of a major farm. The aim is to close the nutrient cycles, generate energy for the farm utilities and reduce GHG emission. Depending on pricing situation for the energy, the energy produced is either used to replaced energy from grids, sold to the grid, or upgraded to produce biomethane for tractors and other farm machinery.

6.6.1.3 Centralized - Scale of Biogas Plants

In centralized biogas plants, the technologies applied is usually complex than agricultural substrate operated biogas plant. Substrates are often collected from different sources and the mixture may contain diverse materials from municipalities, agriculture and industry. The choice of technology depends on:

- Aims of the processing (*e.g.* energy production, stabilization of waste materials, fertilizer production, reduction of environmental load)
- Costs for investment and operation
- Raw materials available
- Subsidy systems available etc.

A centralized biogas plants is shown in Figure 6-5. The economy of scale offers more return on investment which makes them more attractive than smaller biogas plants. Currently, centralized and large farms plants have two or three digesters with several thousands of cubic meters in volume, some with CHP and other for biomethane.

Figure 6-5 Centralized biogas plant

6.7 Main Components of Biogas Plants

A biogas plant consists of several units. The design of biogas plants depends mostly on the types and amounts of substrate supplied. The major processing steps in a biogas production are illustrated in Figure 6-6. The difference between wet and dry AD is only theoretical, since microbiological activity biogas production always take place in fluid media. The limit between wet and dry digestion is determined by the ability to pump the substrate.

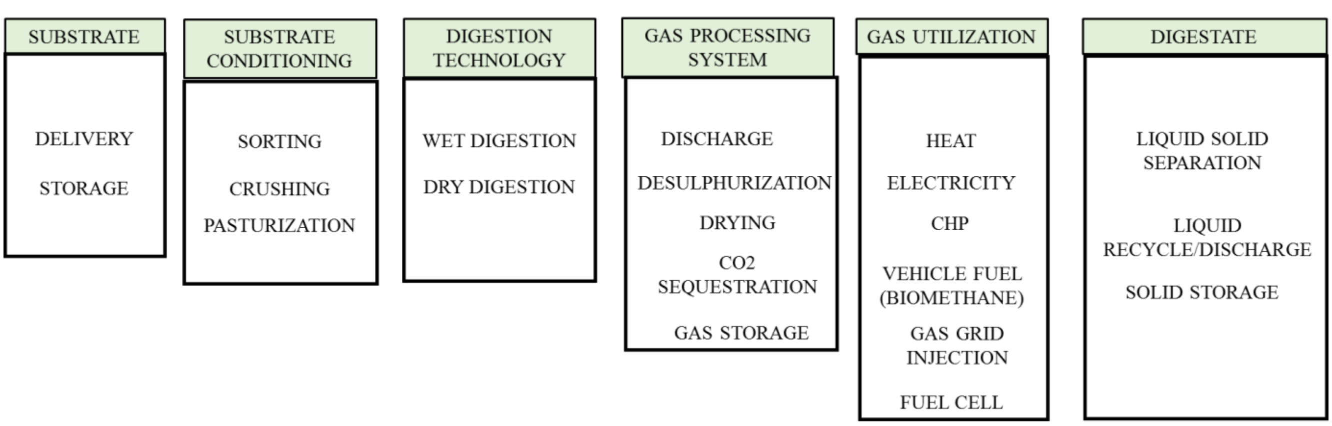


Figure 6-6 Main processing steps of anaerobic technologies

6.7.1 Feedstock Handling

6.7.1.1 Receiving Unit of Substrate

Efficient transport and supply of substrate (food, crop by-products and manure) is important running a biogas plant. Robinson deep landfill site collects waste and transport mechanisms are already in place.

6.7.1.2 Conditioning of Feedstock

The main aim of conditioning is to increase feedstock digestibility, fulfill the demands of sanitation and increase biogas yield. Conditioning of feedstock includes:

1. **Feedstock Sorting and Separation of Unwanted Material.**

This is necessary and an initial step for sorting and separating impurities and unwanted materials from the feedstock substrate. Silage is considered as a clean feedstock type, while household wastes and manure contains stones, sand and other physical impurities. These impurities are usually separated by sedimentation in storage tanks (in the case of sand) and they have to be removed from the bottom of the tanks from time to time. sometimes, could use pre-tank equipped with special grills, which are able to retain stones and other physical impurities before pumping the substrate into the equipped main storage tank. These impurities could be removed by a separate collection system of household wastes into different homogeneous groups e.g. metals, papers, organic, plastic etc.) or they can be removed from a bulk collected wastes by using mechanical sorters (Screens, magnetic separation, rotating trommels etc.) and manual methods (use only for small quantities of wastes).

2. **Crushing**

Crushing of feedstock material aims to prepare the surfaces of the particles for biological decomposition and the subsequent methane production. In general, the decomposition process is increases with size reduction. Size reduction of particles can take place by biological and /or mechanical ways.

3. **Mashing**

Mashing of substrate is necessary in order to obtain substrate with a higher moisture content, which can be handled by pumps. The advantage of using digestates for mashing lies in the reduction of water consumption and in the inoculation of the substrate with AD micro-organisms from the digester.

6.7.1.3 Storage of Substrate

Storage of substrate mainly aims to compensate the seasonal fluctuations of substrate supply. It is also facilitates mixing of different co-substrates for continuous feeding of the digester. The type of storage depends on the type of substrate. Types of stores can be mainly classified into bunker silos for solid substrate (e.g. food stock Figure 6-7 left) and storage tanks for liquid feedstock (*e.g.* slurries and liquid manure Figure 6-7 right). Bunker silos can store substrate for approximately 6 months to one year while storage tank for several days to months. The dimensioning of the storage facilities is determined by delivery intervals, the quantities to be stored and the daily amounts fed into the digester.

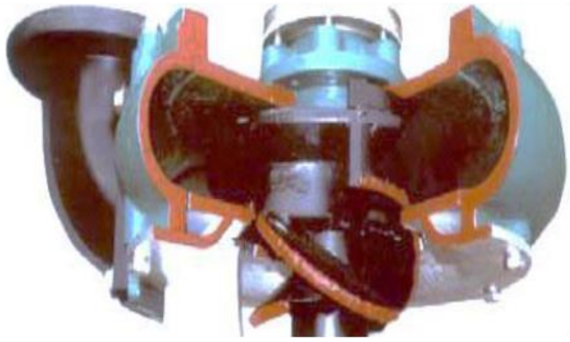
Figure 6-7 Bunker silo made of concrete and covered by plastic foils (left) and Slurry tank (right)

6.7.2 System of Feeding

After storage and pre-treatment of substrate, it is feed into the digester. There are two categories of substrate, pumpable and non-pumpable. The pumpable substrate category includes liquid organic wastes and animal slurries (*e.g.* flotation sludge, fish oil, cattle wastes). Feedstock types which are non-pumpable (e. g. fibrous materials, maize silage, grass, manure with high straw content) can be poured by a loader into the feeding system and then fed into the digester by use of a screw pipe system.

6.7.2.1 Pumps

Pumps are used to transfer the pumpable substrate from the storage tank to the digesters. There are two types of pumps that are frequently used: centrifugal pumps (Figure 6-8 left), and positive displacement pumps (Figure 6-8 right) and progressing cavity pumps (Figure 6.17). Centrifugal pumps are often submerged, but they can also be positioned in a dry shaft next to the digesters. Positive displacement pumps are more resistant to pressure than centrifugal pumps. They are self-sucking, works in two directions and can reach relatively high pressures, with a short conveying capacity. However through their lower price, centrifugal pumps are more frequently chosen than positive displacement pumps.



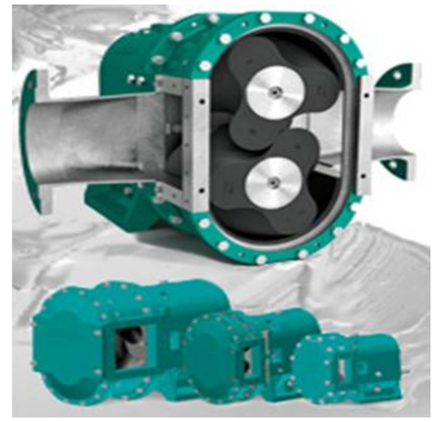


Figure 6-8 Centrifugal pump (left) and rotary lobe pump (right)

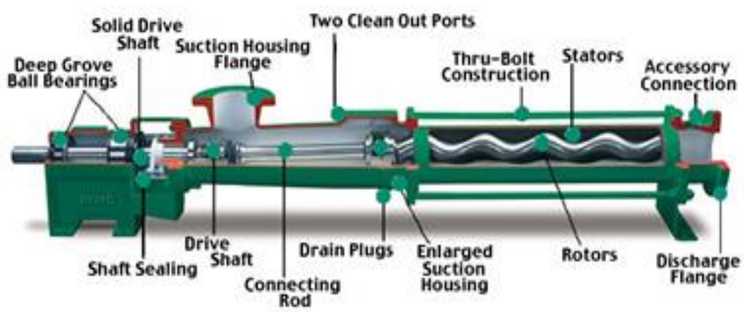


Figure 6-9 Cross section of progressing cavity pump

The selection of appropriate pumping technology and pumps depends on the characteristics of the substrate to be handled by pumps (type of material, particle size, DM content, and level of preparation). Pressure pipes, for mixing or filling, should have a diameter of at least 150 mm, while pressure free pipes, like outlet pipes or overflow, should have at least 200 mm for transporting manure and 300 mm if the straw content is high. The pumps should be equipped with stop-valves like in Figure 6-10. This allows emptying and feeding of digesters and pipelines. In many cases the entire feedstock transport within the biogas plant is realized by one or two pumps, located in a pumping station shown in Figure 6-11.

Figure 6-10 Stop valve (left) and pumping system (right)

Figure 6-11 Pumping systems

6.7.2.2 Feeding Equipment of Solid Feedstock

The feeding system of solid substrate (*e.g*. grass, manure, maize silage, high straw content, vegetable residues etc.) consists of transport equipment (*e.g*. tractor and loaders), which transports substrates from bunker silo to containers, and a conveying system. Screw conveyors (Figure 6-12) can convey substrate in all directions. For optimal operation, coarse substrate should be crushed, in order to be fitted into the screw windings. There are three different systems of screw conveyors which are commonly used: wash-in shaft, feed pistons and feed conveyor screws. They are illustrated in Figure 6-13.

Figure 6-12 Screw pipe conveyors

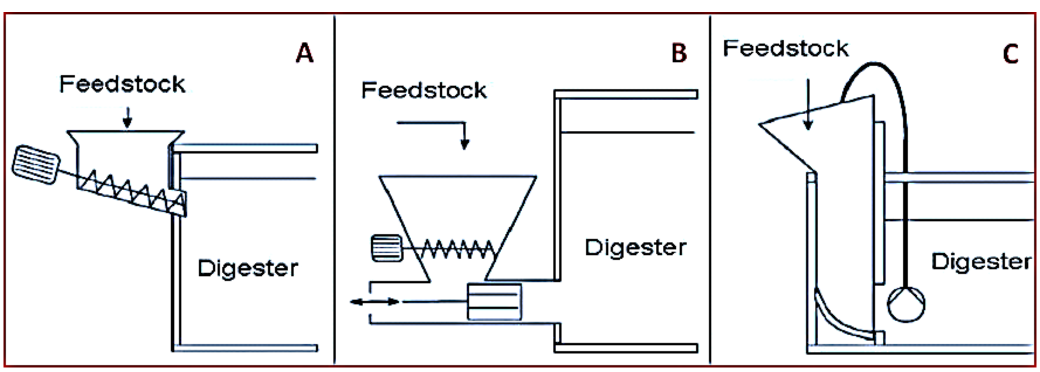


Figure 6-13 A. Wash-in shaft, B. feed piston and C. feed conveyor system for feeding feedstock into the digester

1. Wash-in Shaft:

Wash-in shafts allow large quantities of substrate to be delivered any time, directly to the digester (Figure 6-13 A).

2. Feed Pistons:

Feed pistons (Figure 6-13 B) uses to feed the substrate directly into the digester by hydraulic cylinders. It pushes the substrate through an opening in the wall of the digester. This system is use for reducing the risk of floating layer formation. This system is equipped with counter rotating mixing rollers for crush long fiber materials like air-dried silage.

3. Feed Screws Conveyor:

Feed screw conveyor shown in Figure 6-13 C is used to feed the substrate under the level of the liquid in the digester. This system has the advantage of preventing gas leaking during feeding process. This system sometimes is equipped with mixing and crushing tools as shown in Figure 6-14.

Figure 6-14 Feeding container equipped with screw conveyor, mixing and crushing tools

6.7.3 Digester Heating System

One of the most important parameter for high biogas production is to keep temperature constant in AD process. Temperature fluctuations must be limited, fluctuations of temperature lead to imbalance of the microbial in AD process, and in worst scenario lead to failure of the process.

The reasons of temperature fluctuations are:

- Formation of various temperature layers due to inadequate stirring and insufficient heating system.
- Extreme outdoor temperature.
- Power system Failure.
- Addition of fresh substrate, with a temperature different from the process temperature.

Digesters must be heated by external heating sources and isolated in order to achieve and maintain a constant temperature of AD process and to compensate for the heat losses.

The substrate heating can be done during the feeding process (pre-heating) or inside the digester, by heating system (Figure 6-15). Pre-heating the substrate during feeding has the merit of avoiding temperature fluctuations inside the digester. Many biogas plants use a combination of both types of substrate heating.

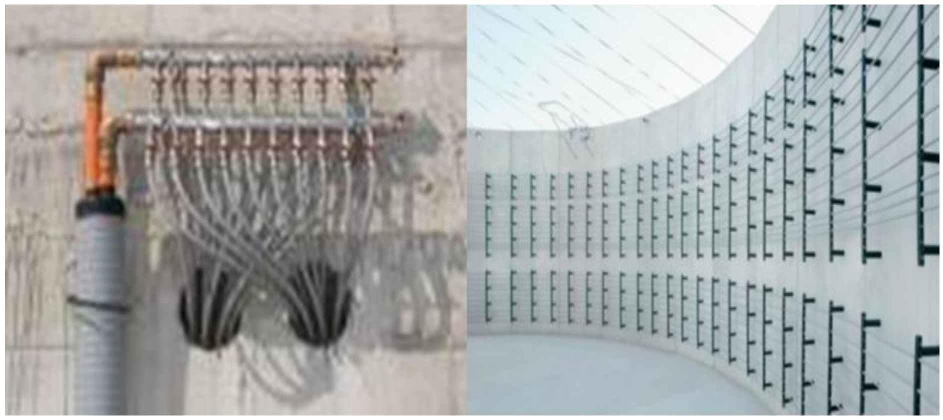


Figure 6-15 Heating system of digester

6.7.4 Digesters

Digesters are considered as the core of biogas production system. This is where the decomposition of substrates occurs, in absence of oxygen for production of biogas. In European countries, temperature tends to be low and thus the anaerobic digesters have to be insulated and heated. There are a various types of on-farm biogas digesters, which can be made of different materials such as concrete, brick, plastic, steel, shaped like silos, basins, troughs or ponds, and they may be placed on the surface or underground. The size of digesters varies from few cubic meters in the case of small household digesters to several thousands of cubic meters, like in the case of large commercial digesters.

6.7.4.1 Wet Anaerobic Digestion

Wet digestion has been previously discussed. Batch and continuous processes are possible. The following digester technologies are suitable for wet digestion.

1. **Covered Lagoon Digester**

It consists of a rectangular earthen lagoon covered with a flexible membrane to collect biogas as shown in Figure 6.24. Table 6-1 presents advantages and disadvantages. Substrate needs to be thin (contains less than 3 % of DM). The covered lagoon digester may be mixed with recirculation but is generally not mechanically mixed. Feedstock enters at one end, pushing substrate out through an overflow pipe, maintaining a consistent liquid level. The lagoons operate at psychrophilic temperature or ground temperatures. Consequently, the reaction rate is affected by seasonal variations in temperature. The residence time of substrate (HRT) is ranges from 20 to 200 day.

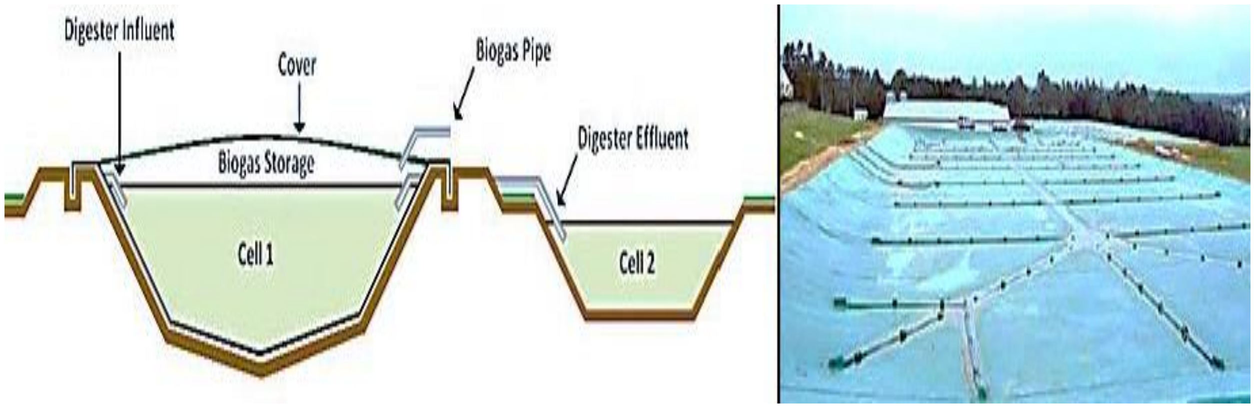


Figure 6-16 Covered lagoon digester

Main components:

- Usually two lagoons: primary (covered) and secondary (volume storage).
- Solids separator.
- Biogas utilization system.
- Floating lagoon cover.

Table 6-1 Advantages and disadvantages of covered lagoon digester

Advantages	Disadvantages
• Inexpensive. • Low technology applied compared with more mechanical systems. • Simple and easy to install.	• Poor mixing of feedstock. • Requires large significant area. • Poor solids degradation. • Poor yield of biogas. • Has a high HRT. • Nutrients and solids accumulate in bottom of lagoon, which lead to reducing useable volume of lagoon. • Bacteria wash out.

2. Plug flow Digester

The plug flow digester can be a vertical or horizontal reactor. Usually horizontal digester consists of rectangular tank that is half buried with a hard or flexible membrane cover installed to collect the biogas produced (Figure 6-17). The feedstock needs to be relatively thick (contains 8 – 12 % of DM) to ensure that feedstock movement maintains the plug flow effect. These digesters are generally not mixed mechanically. Feedstock enters at one end, pushing older substrate forward until it to the exits. Some systems will re-circulate substrate from the end of tank to inoculate the new material entering and then speed up the degradation process. The residence time of substrate (HRT) ranges from 20 to 40 days.

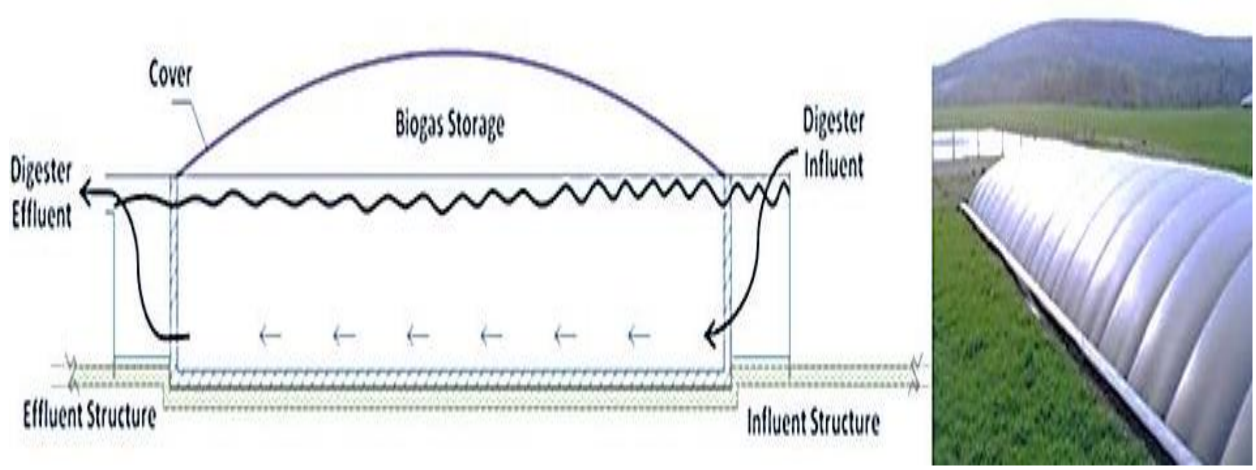


Figure 6-17 Plug flow digester

Main components:

- Mixing tanker
- Digester equipped with heat exchanger and biogas recovery system
- Effluent storage structure
- Biogas utilization system.

Table 6-2 Advantages and disadvantages of plug flow digester

Advantages	Disadvantages
• Inexpensive • Fit for livestock manure digestion • Produces high quality fertilizers. • Simple to install and operate • Works well with scrape systems (systems of manure collection from Corals)	• Feedstock DM must be between 8-12 %. • Poor yield of biogas • Susceptible to contaminants (cannot be used with sand bedding) • Poor mixing of feedstock • Nutrients and solids accumulate in bottom of digester, which lead to reducing useable volume of digester • Poor solids degradation • Bacteria wash out. • Membrane-top subject to weather (wind and snow)

3. **Complete Mix Digester**

A complete mix organic digester also known as continuous stirred tank reactor (CSTR, Figure 6-18). A single (one-stage) CSTR is the most common on-farm digester type with continuous feeding of energy crops and/or manure (*e.g.* grass silage or maize). The biogas plant with CSTR technology may also be two- or multi-stages. CSTR usually vertical circular tanks with hard or flexible membrane cover that store biogas. Tanks can be designed in a vertical mode (top mounted mixer) or flat (side mixers) configuration mode. CSTR are always mechanically stirred. The fresh feedstock enters the tank and is immediately mixed with the existing, partially digested material. Biogas production proceeds without any interference from the loading and unloading of the waste material. To optimize the digestion process of the anaerobic bacteria, the digester should be kept at a constant temperature. Typically, a portion of the biogas generated is used to heat the contents of the digester, or the coolant from a biogas-powered generator is returned to a heat exchanger inside the digester tank. The residence time of substrate (HRT) ranges from 20 to 80 days. Advantages and disadvantages of complete mix digesters is presented in Table 6-3.

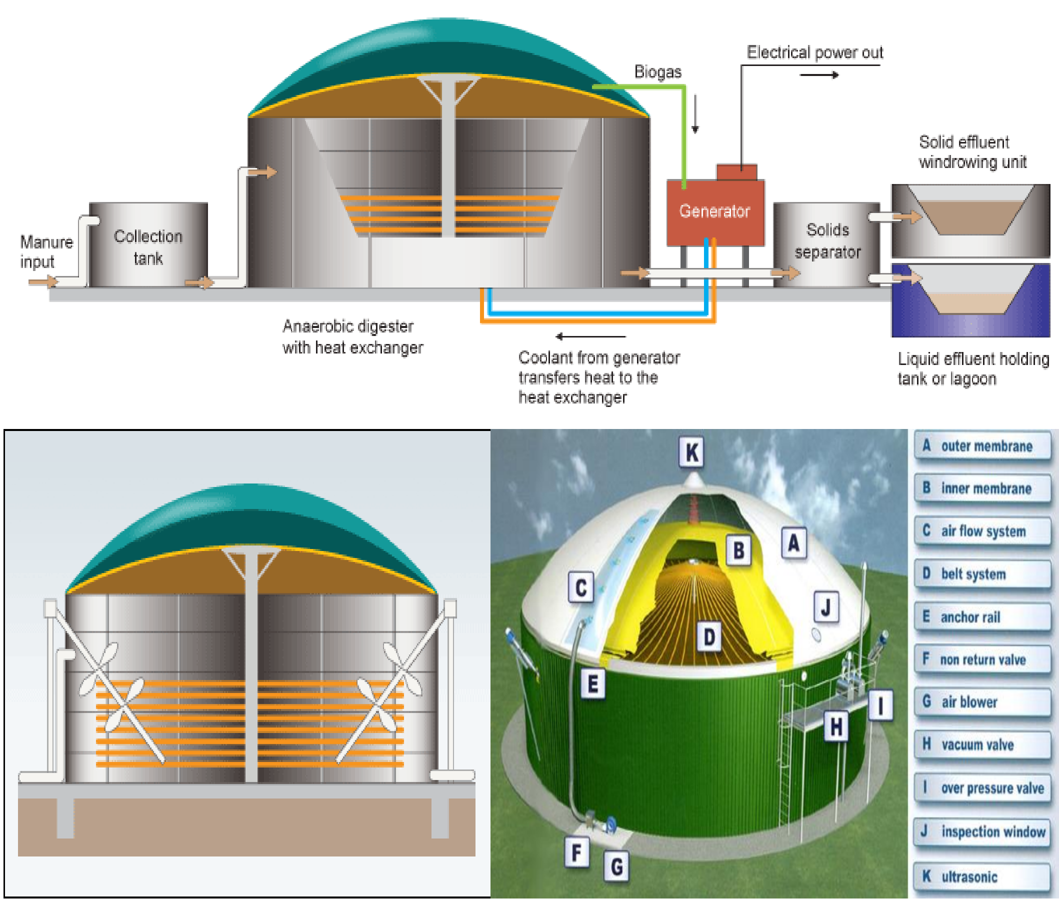


Figure 6-18 Complete mix organic digester

Main components:

- Mixing tank
- Digester equipped with mixing, heating and biogas recovery systems
- Effluent storage system
- Biogas utilization system.

Table 6-3 Advantages and disadvantages of complete mix digesters

Advantages	Disadvantages
• Efficient • Good mixing of feedstock • Can digest different feedstock contains different levels of dry matter • Good solid degradation • Can digest energy crops and by-products with animal manure • Works well with flush and scrape systems (systems of manure collection from Corrals) • Can be used with either flush or scrape systems • The manure tanks, which already exist in farms could be converted to biogas digesters by equip them with isolation, stirring and heating systems which leading to construct cheap digester of biogas	• Relatively expensive • Requires mechanical mixing system • No guarantee on how much time the material remains in the tank (HRT) • Bacteria wash out.

4. **Fixed film Digester**

A fixed film digester as shown in Figure 6-19 is also called attached growth digesters or anaerobic filters. It usually consists of a column packed with media, such as small plastic rings or wood chips. Methane-forming microorganisms grow on the media called a bio-film. Usually, effluent is recycled to maintain a constant upward flow. A solids separator is needed to remove particles from the manure before feeding the digester. Efficiency of this system depends on the efficiency of the solids separator. Therefore, influent manure concentration should be adjusted to maximize separator performance, (usually, 1 to 5 % total solids concentration of influent manure). The residence time of substrate (HRT) ranges from 1 to 20 days. The advantages and disadvantages are presented in Table 6-4.

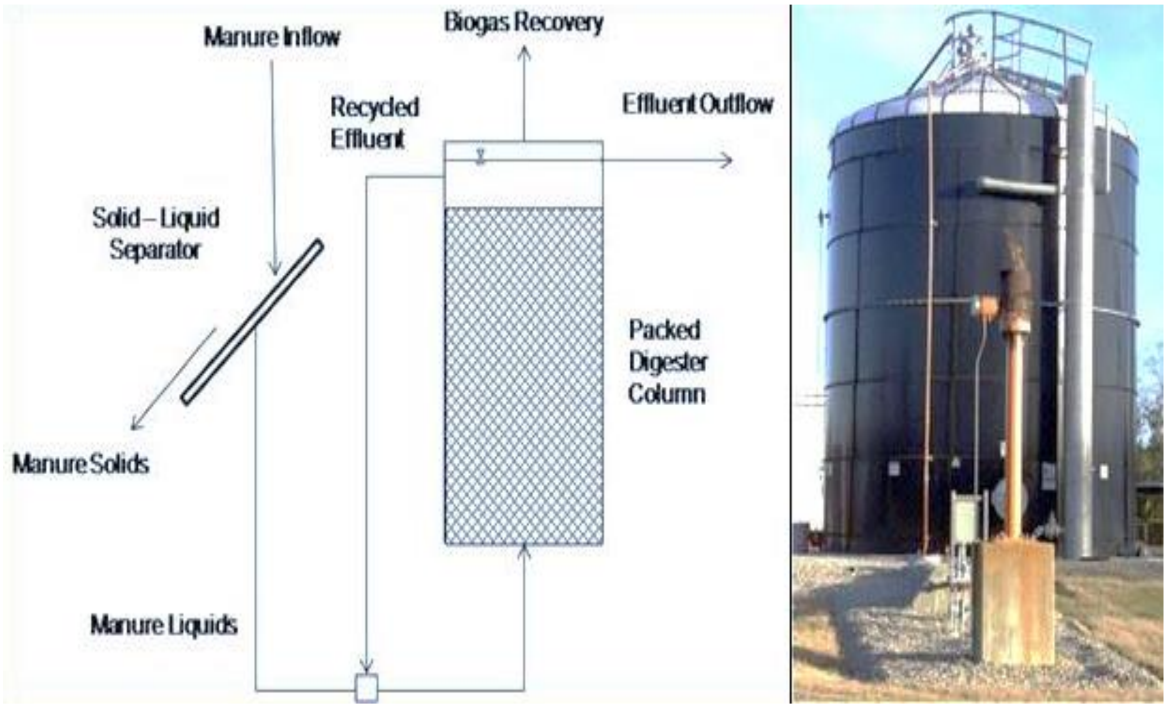


Figure 6-19 Fixed film digester

Main components:

- Solids separator
- Influent recycling pumps
- Digester system
- Biogas utilization system.

Table 6-4 Advantages and disadvantages of fixed film digesters

Advantages	Disadvantages
• Efficient • Works with dilute feedstock • Low HRT (< 20 days) • Good solid degradation • Low bacteria wash out	• Expensive • Requires efficient system of solids separation • Cannot digest feedstock contains high concentration of solids • Susceptible to plugging problems by manure solids • Some potentials of biogas production are lost due to removing manure solids

5. **Up-flow Anaerobic Sludge Blanket (UASB):**

UASB is a circular tanks with hard tops, but can be found as a rectangle tanks (Figure 6-20). They are mixed by recirculation of influent. UASB have been designed for agri-food waste water treatment. Wastewater is distributed into the tank at appropriately spaced inlets. The wastewater passes upwards through an anaerobic sludge bed where the microorganisms in the sludge come into contact with wastewater substrates. The sludge bed is composed of microorganisms that naturally form granules (pellets) of 0.5 to 2 mm diameter that have a high sedimentation velocity and thus resist wash-out from the system even at high hydraulic loads. The upward motion of released biogas bubbles causes hydraulic turbulence that provides reactor mixing without any mechanical steering. At the top of the reactor, the water phase is separated from sludge solids and gas in a three-phase separator (also known the gas-liquid-solids separator). The three-phase-separator is commonly a gas cap with a settler situated above it. Below the opening of the gas cap, baffles are used to deflect gas to the gas-cap opening. The residence time of substrate (HRT) is from 0.5 to 2 days. The advantages and disadvantages of UASB are presented in Table 6-5.

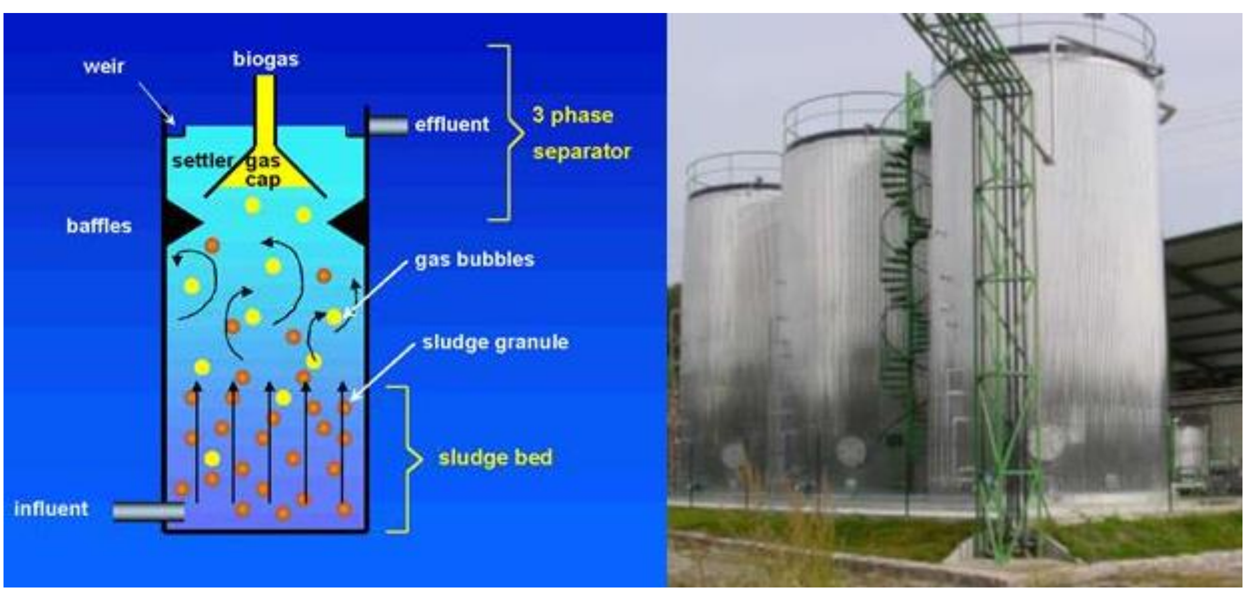


Figure 6-20 Up-flow anaerobic sludge blanket digester (UASB)

Main components:

- Mixing tank;
- Digester equipped with heating and biogas recovery systems;
- Effluent storage system;

- Biogas utilization system.

Table 6-5 Advantages and disadvantages of Up-flow anaerobic sludge blanket digester (UASB)

Advantages	Disadvantages
• High efficient • Good retention of bacteria • Can treat heavy loaded wastewater	• High expensive • Complex operating • Not designed to accept high concentrations of suspended solids • Does not digest fats. • Not widespread for agricultural applications

6.7.4.2 Dry Anaerobic Digesters

Dry digesters are systems containing substrate(s) that are not pumpable (contains 20 – 40 % dry matter or more) and the digesters equipped with the feeding equipment of solid feedstock. Both batch and continuous digestion are possible.

- **Batch System for dry AD**

Batch operation is usually used for raw materials with high TS content, such as solid manure. A garage type is the most common batch reactor (Figure 6-21). It is filled with a mixture of new feedstock and digestate (for give inoculum) by using *e.g.* a front loader and then closed for biogas producing under airtight conditions. No stirring of feedstock, hence, leachate is collected via chamber drain and sprayed back on top of the pile to provide a mixing or inoculating effect. Digestion occurs at mesophilic temperatures at 34 – 37 °C, which are regulated through heated floors and walls. Finally opened and emptied just to start a new cycle again with new feedstock. As the biogas production varies depending on the stage of the operational cycle, it is usual to have at least three parallel batches in different stages of operation: one being filled, one in biogas producing phase and one being emptied. The residence time of substrate (HRT) ranges from 20 to 30 days.

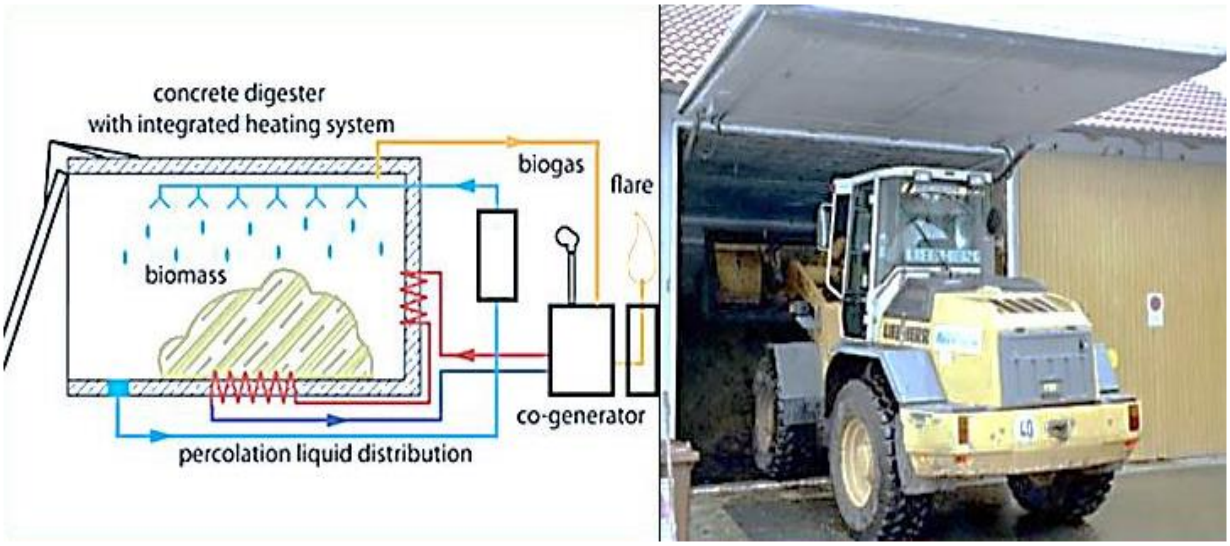


Figure 6-21 Batch type dry anaerobic digester

Main components:

- Digester equipped with a system of draining, recycling and spraying of leachate, heating and biogas recovery systems
- Digestate storage system
- Biogas utilization system.

Table 6-6 Advantages and disadvantages of batch dry digestion

Advantages	Disadvantages
• Efficient • Can digest energy crops and by-products with animal manure • Can digest dry feedstock contains high levels of dry matter • No wash out of bacteria • Good solid degradation	• High expensive • No guarantee on how much time the material remains in the tank (HRT) • Uneven gas production and lack of stability in the microbial population • Need to 3 digesters -at least- works in parallel (at different stages of digestion) to overcome the volatility of biogas production

Continuous Systems for dry AD

In continuous dry digesters, feedstock is constantly fed into the digester. The substrate moves through the digester either by the pressure of the newly feed substrate or mechanically which pushing out the digested material. Unlike batch-type digesters, continuous digesters produce biogas without much interruption and biogas production is constant and predictable. Continuous digesters could be either vertical or horizontal and could be multiple or single systems. Completely mixed digesters are typically vertical digesters while plug-flow digesters are horizontal.

1. **Vertical Dry Digesters:**

Vertical cylindrical digester (Figure 6-22) is fed from the top side with chopped substrate and where digested digestates are removed from the bottom. Fresh substrate is processed into small pieces and mixed with digested material and fed to the digester using a screw feeding system to ensure bacterial inoculation presence at the top of the digester. There is a vertical plug flow from the top to the bottom. A screw removes material from the bottom. The residence time of substrate (HRT) ranges from 20 to 40 days.

Figure 6-22 Vertical dry digester

Main components:

- Digester equipped with feeding equipment of solid feedstock, heating and biogas recovery systems
- digestate storage system
- Biogas utilization system.

Advantages	Disadvantages
• Efficient • Digester has a relatively small size compared with wet digesters systems and produce high biogas yield	• High expensive • Has a complex mechanical structure and maintenance

• Can digest dry feedstock contains high levels of dry matter • Alternative to traditional production method of smelly composting, and producing high quality compost.	• Feedstock needs to size reduction by chopping for accelerating digestion • Poor Solids degradation • No mixing of substrate lead to reduction the potentials of biogas yield

2. Horizontal dry digesters:

Horizontal digesters (Figure 6-23) consist of horizontal cylindrical shape unit and equipped with a heating system, manure pipes, gas dome and stirring system. This type of digesters is usually manufactured in one piece of stainless steel, so that they are limited in volume and size. The standard type for small scale digester is a horizontal steel tank with volume ranging from 50 to 150 m^3, which uses as a main digester for small biogas plants or as pre-digester for larger plants, for increase the digestion efficiency of main digester. There are also alternative digesters made of concrete, with volume up to 1000 m^3. Horizontal digesters can also run in parallel, in order to produce more biogas yield. Horizontal continuous flow digesters are usually used for dry substrate like grass, chicken manure, manure, maize silage, manure or high straw content. The residence time of substrate (HRT) ranges from 20 to 40 days.

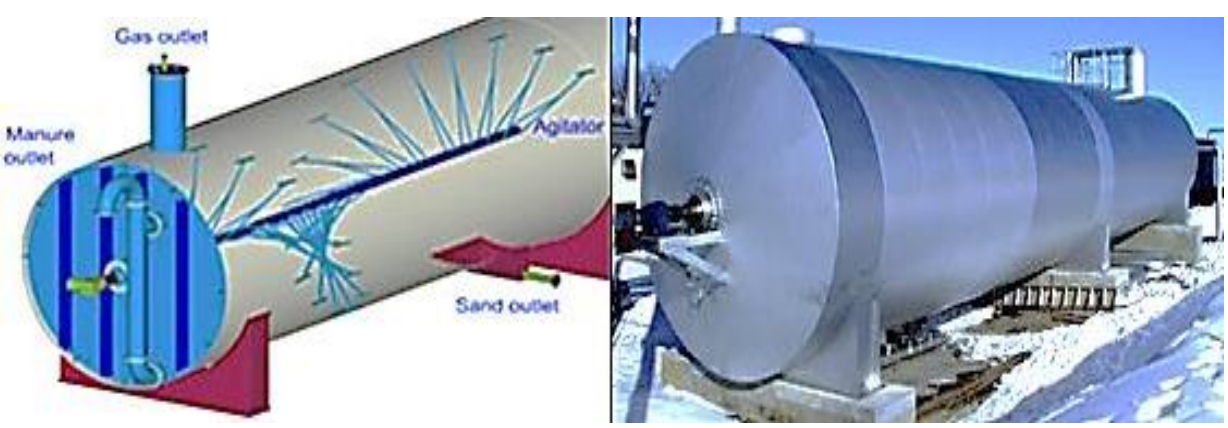


Figure 6-23 Horizontal dry digester

Main components:

- Digester equipped with feeding equipment of solid feedstock, stirring, heating and biogas recovery systems
- digestate storage system
- Biogas utilization system.

Table 6-7 Advantages and disadvantages of horizontal dry digestion

Advantages	Disadvantages
• Efficient • Alternative to traditional production method of smelly composting, and producing high quality compost • Can digest dry feedstock contains high levels of dry matte • Digester has a small size compared with wet digesters systems and produce high biogas yield • Good mixing of feedstock • Good Solids degradation	• High expensive • Has complex mechanical structure and maintenance • Feedstock needs to size reduction by chopping for accelerating digestion • Has a limited productivity

Table 6-8 Comparison of various digester types

Technology	Digester type	Feedstock type	HRT (days)	Biogas yield	Technology level
Wet digestion	Covered lagoon	Thin manure	20-200	Poor	Low
	Plug flow	Think manure	20-40	Poor	Low
	Complete mix	Liquid and Solid	20-80	Good	Medium
	Fixed film	Liquid	1-20.	Good	High
	UASB	Liquid	0.5-2	Good	High
Dry digestion	Batch	Agricultural and municipal feedstock	20-30	Good	Medium
	Vertical		20-40	Good	High
	Horizontal		20-40	Good	High

6.7.5 Stirring Systems

The indirect stirring could occur by feeding of fresh substrate and the subsequent thermal convection streams as well as by the up-flow of gas bubbles. Indirect stirring is not sufficient for optimal operation of the digester; active stirring must be applied by the use of hydraulic, mechanical, pneumatic equipment. Up to 90 % of biogas plants use mechanical stirring equipment for increasing the digestion efficiency and biogas yield.

The substrates inside the digester must be stirred on a several occasion daily for mixing the new substrate with the existing substrate inside the digester. Moreover, stirring prevents formation the layers of floating sediments thus facilitates the upflow of gas bubbles and homogeneity distribution of heat and nutrients through the whole mass of substrate.

6.7.5.1 Mechanical Stirring

According to rotation speed of the stirrers, mechanical stirrers can be fast, medium and slow running stirrers. Submersible motor propeller stirrers shown in Figure 6-24 are frequently used in vertical digesters. They are completely immersed in the substrate and usually have two or three wings, geometrically optimized propellers. Paddle stirrers have a horizontal, vertical or diagonal axis (Figure 6-25, Figure 6-26 and Figure 6-27). The motor is positioned outside the digester. Junctions, where the shaft passes the membrane roof, digester ceiling or the digester wall, have to be tight.

Figure 6-24Submersible motor propeller stirrer

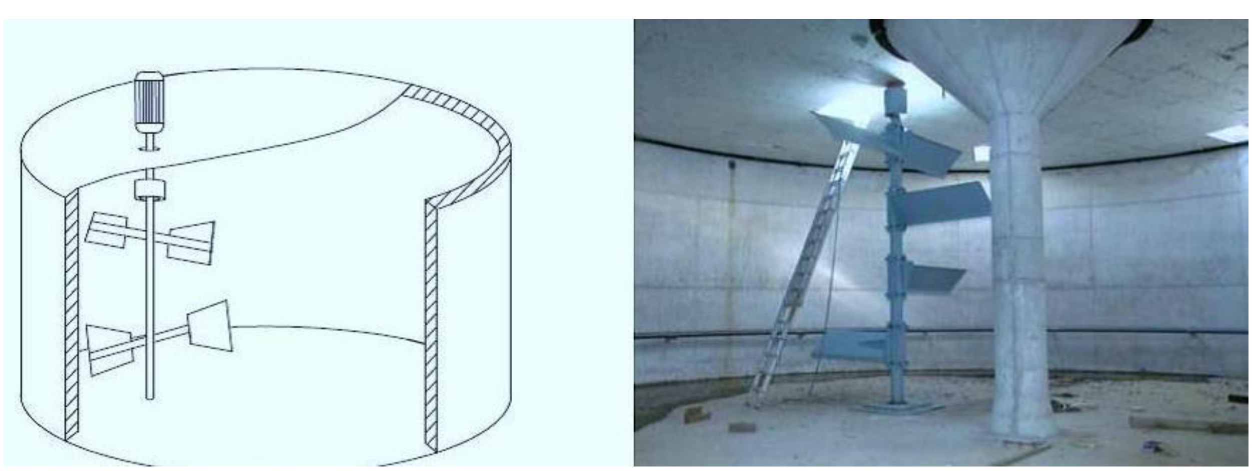


Figure 6-25 Vertical hanging paddle stirrers

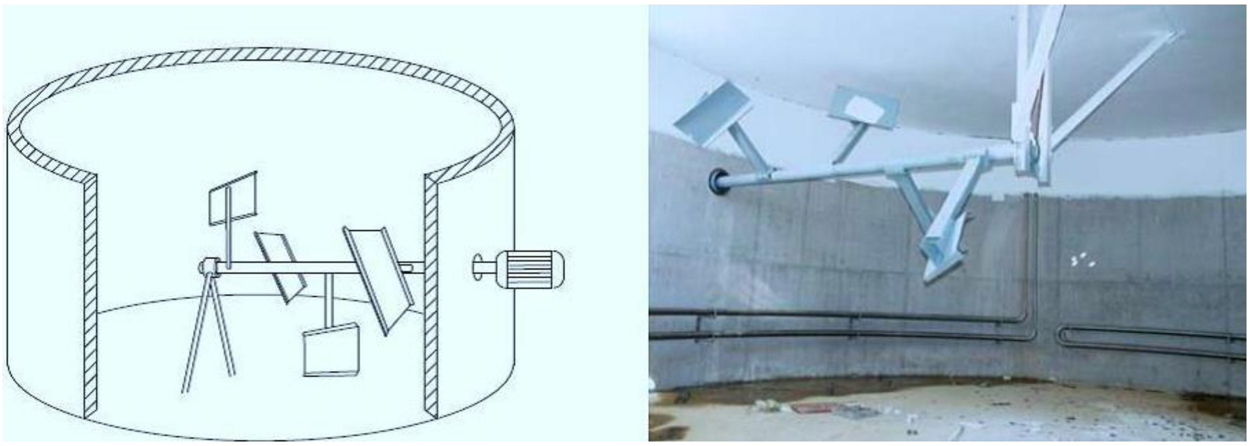


Figure 6-26 Horizontal hanging paddle stirrers

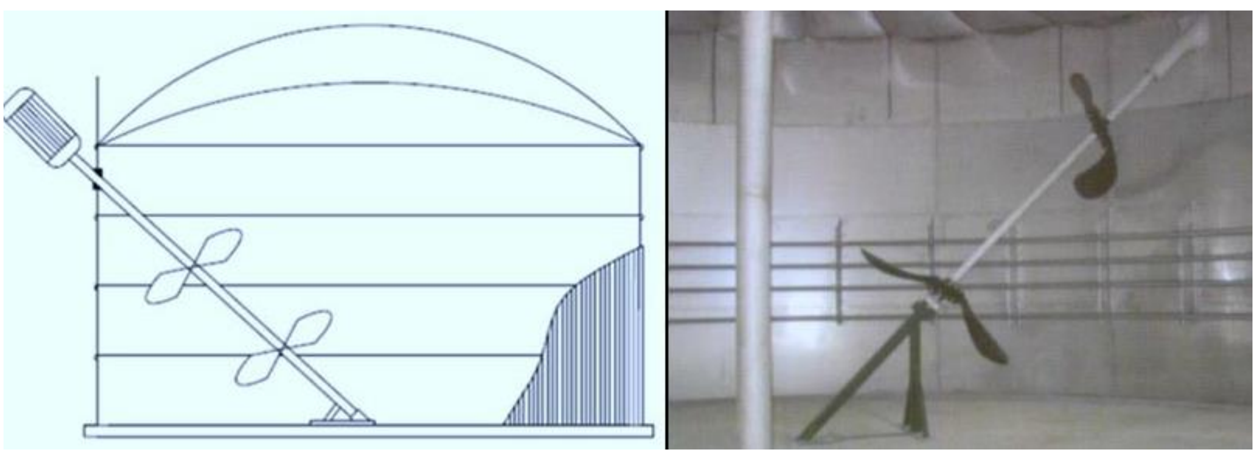


Figure 6-27 Diagonal paddle stirrers

6.7.5.2 Hydraulic Stirring

Hydraulic stirring system shown in Figure 6-28 works by pressing the substrate and by pumping through horizontal or additional vertical vents into the digester. Hydraulically stirred systems have the advantage that the mechanical parts of the stirrers are placed outside the digester, subject to lower wear and can be easily maintained. Hydraulic stirring is appropriate for the destruction of floating layers of sediments.

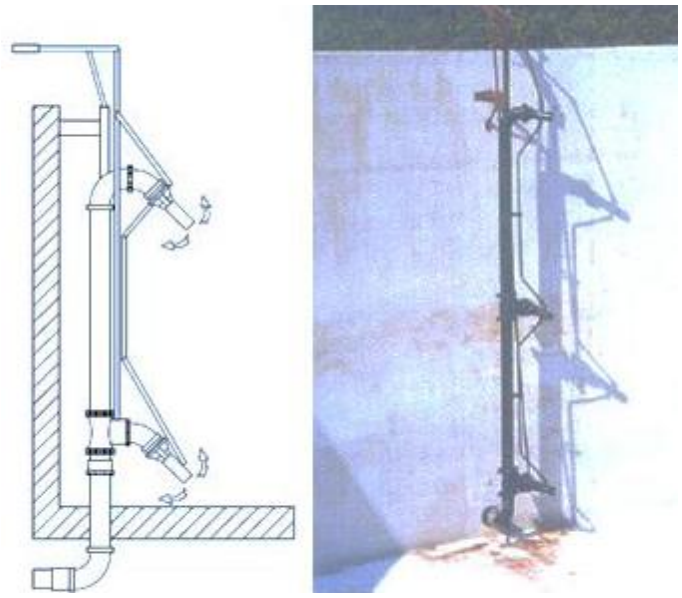


Figure 6-28 Hydraulic Stirring System

6.7.5.3 Pneumatic Stirring

Pneumatic stirring system shown in Figure 6-29 uses the produced biogas, by injection of the biogas from the bottom of the digester through the mass of the substrate. The bubbles of rising gas causes a vertical movement and stirs the feedstock. Pneumatic stirring is not frequently used in agricultural biogas plants, as the technology is not appropriate for destruction of floating layers of sediments.

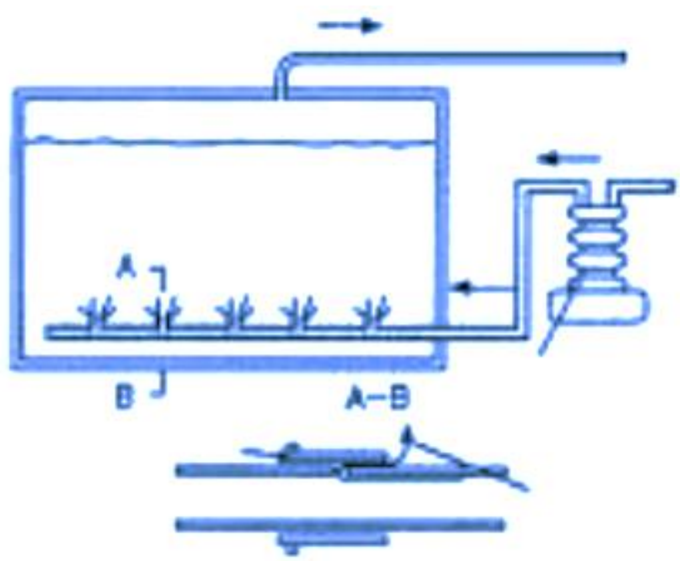


Figure 6-29 Pneumatic stirring system

6.7.6 Biogas Storage

A biogas storage system is essentially required to provide a constant gas pressure to the CHP unit. Biogas is typically generated at unstable rate during the anaerobic digestion process and the fluctuation of biogas production increases when in homogeneous substrates are digesting; such as agricultural residues and food wastes. Correct selection and dimensioning of a biogas storage facility brings substantial contribution to the reliability, efficiency and safety of the biogas plant while ensuring constant supply of biogas and minimizing biogas losses.

The efficient use of digesters aside production of useful gas would be the integration of innovative or non-traditional biogas storage options. The simplest biogas storage is established on top of digesters, using a gas tight membrane (Figure 6-30), which consists of one or two membranes (the external membrane forms the outer shape and the internal membrane seals the digester gas-tight). For safety reasons, biogas holders must be equipped with safety valves under-pressure and over-pressure to avoid unsafe biogas pressure levels (negative or positive) into digester. Usually, a capacity from one to two days is recommended for use the biogas tight membranes.

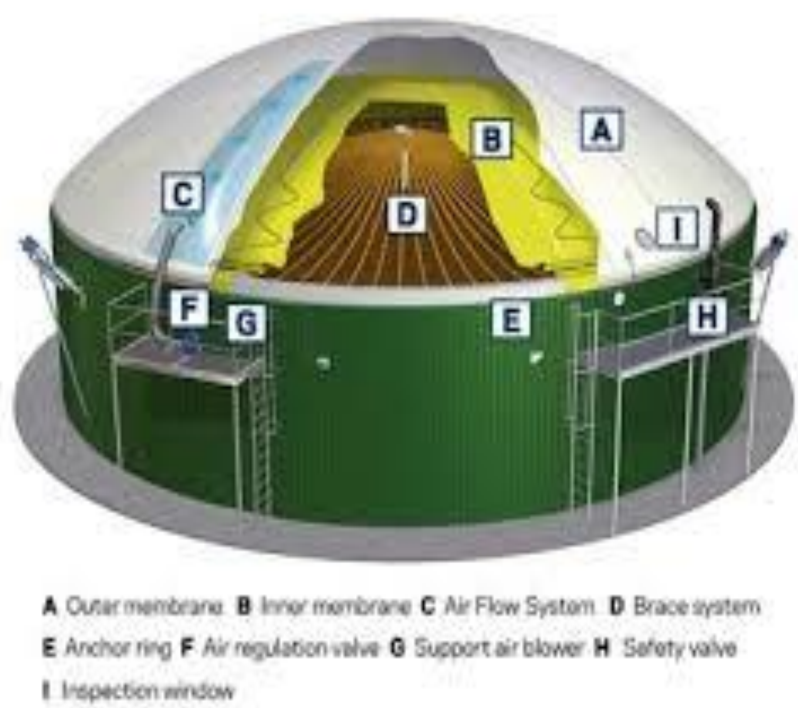


Figure 6-30 Biogas tight membrane

6.7.6.1 Low Pressure Tanks

Low pressure storage facilities of biogas are most commonly use. They have a pressure range from 0.05 to 50 bar and are made of special membranes, which must meet a number of safety requirements. The membrane tanks are installed on the top of the digesters as a covers or as external gas holders or gas domes. External low-pressure tanks can be designed in the shape of membrane cushions (Figure 6-31) or gas balloons (Figure 6-32).

Figure 6-31 Gas cushion tank

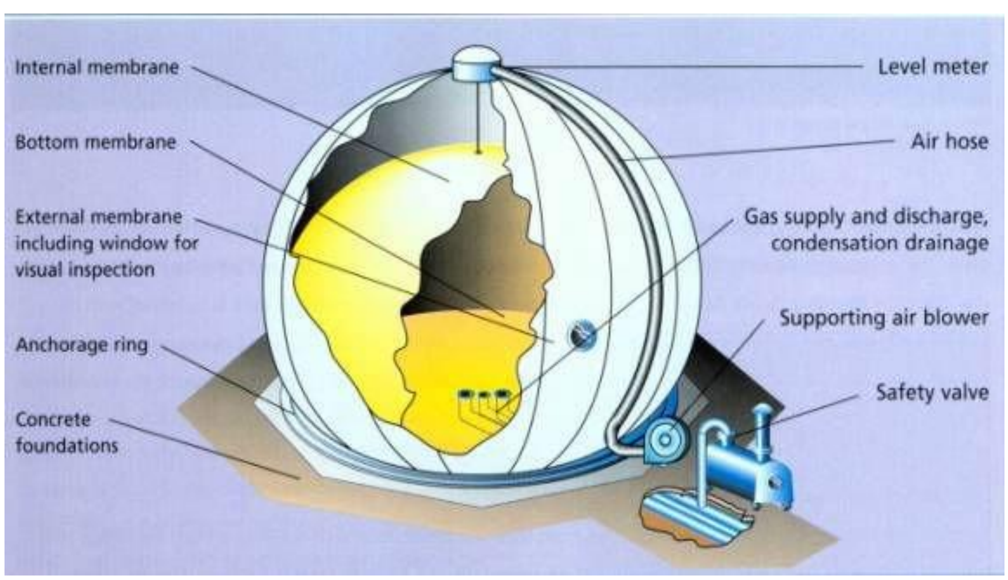


Figure 6-32 Gas balloon tank

6.7.6.2 Medium and High Pressure Tanks

Biogas can also be stored in high pressure tanks made of steel (Figure 6-33) at pressures between 5 and 250 bar. These kinds of storage types have high operation costs and high energy consumption.

Figure 6-33 High pressure tank of biogas

6.7.7 Digestate Storage

After the digestion process is complete, the digestate is dewatered (water removed) and uses as fertilizer. It is transported away from the biogas plant, through pipelines or with special vacuum tankers, and temporarily stored in storage tanks placed in the fields. The total capacity of these tanks must be enough to store the production of digestate for several months. Digestate can be stored in lagoon ponds or in concrete tanks, covered by artificial floating layers or natural or by membrane covers (Figure 6-34).

Figure 6-34 Covered Digestate storage tank

6.8 Digester technology Selection

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

6.8.1 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.

- 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.).

6.8.2 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.

6.8.2.1 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.

6.8.2.2 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 design.

6.8.2.3 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.

6.8.2.4 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.

6.8.2.5 Skills and Labour

Biogas technology is sophisticated and hence requires high levels of specialized 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.

6.8.2.6 Standardization

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.

6.8.3 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 summarized 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;

6.8.3.1 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. 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. There are several variations in MCDA techniques used currently employing mathematics and psychology. These include; analytical hierarchy process (AHP), analytical network process (ANP), simple multi-attributed rating technology, case base reasoning, technology identification and selection to mention but a few.

Previous applications of MCDA in technology selection as a decision support (DS) tool include; Kuria and Maringa 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 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.

6.8.4 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.

6.8.4.1 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 summarized in the steps below;

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.

6.8.4.2 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. 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.

6.8.4.3 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.

6.8.4.4 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.

Previous applications of site selection as a decision support (DS) tool include; Ma et al. 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.

6.8.5 Multi-criteria decision analysis

The MCDA technique were employed to select the most suitable biogas digester technology for organic fraction of municipal solid waste (OFMSW) based on:

- Cost of the digester
- Local availability of the digester
- OFMSW suitability
- Temperature regulation ability
- Presence of agitation accessory
- Ease of construction

The digesters investigated include:

- Complete mix- CSTR
- UASB
- Plug flow
- Covered lagoon

- Fixed film

Using MCDA techniques, a pairwise comparison was conducted with criteria been weighted according to the goal of most suitable digester. As presented in Table 6-9, complete mix had the highest total score among the various alternatives and is therefore preferred as the digester of choice.

Table 6-9 MCDA for digester selection

	CRITERIA	Cost		Local Availability		Scalabilty		OFMSW Suitability		Temperature Regulation Ability		Presence of Agitation Accessory		Ease of Construction		
	WEIGHT	0.17		0.18		0.2		0.2		0.1		0.05		0.1		
	Digester Types	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	TOTAL SCORE
1	Complete Mix-CSTR	0.65	0.111	0.80	0.144	0.85	0.170	0.80	0.160	0.80	0.080	0.90	0.045	0.75	0.075	0.785
2	UASB	0.50	0.085	0.75	0.135	0.65	0.130	0.30	0.060	0.75	0.075	0.80	0.040	0.75	0.075	0.600
3	Plug flow	0.70	0.119	0.60	0.108	1.00	0.200	0.40	0.080	0.60	0.060	0.60	0.030	0.75	0.075	0.672
4	Covered Lagoon	0.80	0.136	0.80	0.144	0.40	0.080	0.50	0.100	0.50	0.050	0.30	0.015	0.80	0.080	0.605
5	Fixed film	0.65	0.111	0.70	0.126	0.40	0.080	0.60	0.120	0.70	0.070	0.75	0.038	0.75	0.075	0.619

The project was fixed at 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 0.05. CSTR scored highest with 0.785 and was selected for the design in OFMSW biogas production.

6.8.6 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.

- 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.

7 Biogas Upgrading to Biomethane

7.1 Environmental impact of biogas

When emitted directly to the atmosphere, from landfill sites for example, biogas can be a significant contributor to GHG emissions and thus climate change, as the CH_4 it contains has about 21-25 times the global warming potential of CO_2. GHG like CO_2 and CH_4 absorb energy and prevent the loss of heat to space. In this way, GHG forms a heat blanket making the earth warmer. H_2S is the most toxic gas emitted directly from biogas. It reacts with moisture in the air to form other acidic gases. Some studies suggest that H_2S has carcinogenic potentials. SO_2, NH_3 and NO_x react with moisture and other compounds to form various acidic compounds and ground level ozone. The acidic compounds return to earth in wet form as acidic rain, fog and in dry form as acidic gases. They reduce air quality, cause damages to public health, reduce visibility, lead to acidification and eutrophication of water bodies. Other dangers directly linked to landfills include; soil acidification, harm on sensitive forest and costal systems and accelerated deterioration of materials like paints and artefacts such as buildings, statues and sculptures. Natural occurring ozone reduces the direct impact of ultra-violet rays from the sun but the ground level ozone has been linked to respiratory illness and other health problems. During the combustion of landfill sourced biogas, the nitrogen oxides produced has about 296-298 times the global warming potential of CO_2.

After upgrading, the use of biomethane as fuel in vehicles, offers some positive properties regarding emissions. The combustion of CH_4 in the presence of O_2 will produce CO_2, water and energy (heat). Biomethane create lesser emissions of CO_2, CO, hydrocarbons (HCs), particulates and sulphide compounds when compared to other fossil fuel source like gasoline and diesel but emits more NO_x if sourced from landfills or with considerable concentration of air. Well-to-wheel (WTW) life cycle analysis (LCA) for gasoline vehicles indicated that 170-190 g $CO_{2,eq}$/Km is emitted while for compressed biogas (CBG) vehicles, it ranges from -180-90 g $CO_{2,eq}$/Km depending on the source and type of substrate used to produce the biogas. The fumes from gasoline and diesel contain benzene and toluene which are not present in fumes from biomethane.

7.2 Biomethane Suitability as vehicle fuel

The use of biomethane as transport fuel has been reported to have more economic advantages over its use in power or heating applications. For biomethane to be used as fuel in ICEs, it has been recommended that the concentration of CH4 should be greater than 90%. Table 7-1 compare the key properties of natural gas from an automotive point of view with biogas, for which if biogas is upgraded to biomethane can possess such properties and be considered as a vehicle fuel.

Table 7-1 Raw biogas comparison to natural gas from an automotive point of view

Gas composition	formula	units	Biogas			Natural gas
			Sewage gas	Agricultural gas	Landfill gas	
Methane	CH_4	% by vol.	65.00 - 75.00	45.00 - 75.00	45.00 - 55.00	83.35 - 98.31
Ethane	C_2H_6	% by vol.	<300 mg/Nm³ (mandatory limit in Germany)			0.50 - 8.02
Propane	C_3H_8	% by vol.				0.19 - 2.06
Butane	C_4H_{10}	% by vol.				0.08 - 0.60
Pentane	C_5H_{12}	% by vol.				0.02 - 0.10
Hexane	C_6H_{14}	% by vol.				0.01 - 0.05
Heptane	C_7H_{16}	% by vol.				<0.01
Octane	C_8H_{18}	% by vol.				<0.01
Benzene	C_6H_6	% by vol.	0.00	0.00	0.00	<0.01
Carbon dioxide	CO_2	% by vol.	20.00 - 35.00	25.00 - 55.00	25.00 - 30.00	0.08 - 1.57
Carbon monoxide	CO	% by vol.	<0.2	<0.2	<0.2	0.00
Nitrogen	N_2	% by vol.	3.40	0.01 - 5.00	10.0 - 25.00	0.81 - 10.64
Oxygen	O_2	% by vol.	0.50	0.01 - 2.00	1.00 - 5.00	0.05/3.00
Hydrogen	H_2	% by vol.	Traces	0.50	0.00	0.00
Hydrogen sulphide	H_2S	mg/Nm³	<8,000.00	10.00 - 30,000.00	<8,000.00	5.00
Mercaptan sulphur	S	mg/Nm³	0.00	<0.10 - 30.00	n.a	6.00
Total sulphur	S	mg/Nm³	n.a.	n.a.	n.a.	30.00
Ammonium	NH_3	mg/Nm³	Traces	0.01-2.50	Traces	0.00
Siloxanes		mg/Nm³	<0.10 - 5.00	Traces	<0.10 - 5.00	0.00
Benzene, Toluene, Xylene		mg/Nm³	<0.10 - 5.00	0.00	<0.10 - 5.00	0.00
CFC		mg/Nm³	0.00	20.00 - 1,000.00	n.a.	0.00
Oil		mg/Nm³	Traces	Traces	0	0.00
Gross calorific value	H	kWh/Nm³	6.60 - 8.30	5.50 - 8.30	5.00 - 6.20	10.26 - 11.99
Net calorific value	H	kWh/Nm³	6.00 - 7.50	5.00 - 7.50	4.50 - 5.50	9.27 - 10.85
Normal density	ℓ	kg/Nm³	1.16	1.16	1.27	0.73 - 0.84
Rel. density related to air	d		0.90	0.90	1.10	0.57 - 0.65
Wobbe index	W	kWh/Nm³	7.3	n.a.	n.a.	10.50 - 14.72
Methane number	MZ		134.00	124-150	136.00	ca. 80-99
Relative humidity		%	100.00	100.00	<100	60.00
Dew point	U	°C	35.00	35.00	0.00 - 25.00	$ts<t_{average, bottom}$
Temperature	θ	°C	35.00 - (60)	35.00 - (60)	0.00 - 25.00	12.00

In the interchangeability of gaseous fuels for vehicles, the Wobbe index (W) is a critical factor to be considered. The energy output of fuels with similar Wobbe indices are approximately identical when operated at equal pressure and valve configuration. However, a 5-10% variation in performance is allowed. The uptake of biomethane as vehicular fuel is partly dependent on the degree of success achieved in the deployment of natural gas. The global market for NGV is gaining increased traction due to low cost and environmental benefits of natural gas when compared to gasoline and diesel. Navigant Research group projected that by 2020, NGV on the roadway worldwide will increase from 18 million in 2013 to nearly 35 million. Pakistan, Bolivia, Iran, Bangladesh and Argentina are the top user of natural gas as vehicle fuel as shown in the table below. Pakistan has 3,395 refuelling stations, China, Iran, Argentina and Italy have 2,500; 2000; 1900 and 900 refuelling stations, respectively. At the third quarter of 2014, only 1.3% of 1,307,893,114 vehicles reported in 84 countries are NGVs. In South Africa, less than 0.01% of the over 7 million vehicles use natural gas.

Table 7-2 Countries and natural gas utilization in vehicles

Countries	No. NGV	Total no. of vehicles	%NGV of total vehicles	Average monthly consumption (Million Nm^3)
Argentina	2,487,349	12,400,000	20.06%	447.72
Bangladesh	220,000	1,155,535	19.04%	79.64
Bolivia	300,000	685,653	43.75%	54.00
Brazil	1,781,102	48,899,365	3.64%	320.60
China	3,327,500	140,108,779	2.37%	3,238.20
Colombia	500,000	4,912,963	10.18%	173.45
Egypt	207,617	4,472,945	4.64%	39.41
Germany	97,619	49,283,087	0.20%	21.84
India	1,800,000	81,697,000	2.20%	1,190.00
Iran	4,000,000	14,450,000	27.68%	737.03
Italy	883,000	47,823,333	1.85%	165.20
Nigeria	3,798	7,600,000	0.05%	0.93
Pakistan	3,700,000	4,481,799	82.56%	642.60
Peru	183,786	1,580,698	11.63%	33.11
South Africa	**937**	**7,915,214**	**0.01%**	**0.55**
Sweden	44,322	5,285,597	0.84%	13.60
UK	663	33,639,528	0.00%	0.49

USA	142,000	253,701,808	0.06%	150.80
Uzbekistan	450,000	2,000,000	22.50%	81.00

With approximately 532 metro buses currently operating with the CoJ covering 80 scheduled routes and 130 school routes, the use of biomethane, a substitute to natural gas, as vehicle fuel is being advocated for in the public transport sector. At the C40 climate summit held in Johannesburg in February, 2014, two dual fuel metro buses were show-cased and it was said that by 2016, the city of Johannesburg will have 300 dual fuel buses using 50% biomethane. Figure 7-1 shows some South African bi-fuel MBT and family sized saloon car modified to operate on gasoline and CNG as well as dual fuel Metro buses modified to operate on CNG and diesel. The modified vehicle engines can also run on CBG as an alternative to CNG. Biomethane with at least 32.3 MJ/m^3 HV can be used in many natural gas combined heat and power (CHP) engines with little or no modification. However, most original equipment manufacturer (OEM) of CNG vehicles require a minimum of 34 MJ/Nm^3. Table 7- shows the energy content of different vehicle fuels as compared to biomethane. From Table 7-, the energy content in 1 Nm^3 of biomethane with 100% CH_4 is approximately equivalent to 1.18 litres of gasoline while 1 Nm^3 of natural gas correspond to 1.2 litres of gasoline.

Figure 7-1 Metro buses, Mini bus taxis and saloon car fitted with natural fuelling system

Table 7-3 Energy content of vehicle fuel

Vehicle fuel	Energy Content (MJ)
1 Nm^3 biomethane (97% CH_4 concentration)	34.8
1 Nm^3 of natural gas	39.6
1 litre of gasoline	32.6
1 litre of diesel	35.3
1 litre of E85 (85% ethanol and 15% gasoline)	22.9 (summer, 85% ethanol)
	23.7 (winter, 79.5% ethanol)

7.3 Effects of impurities in biogas on combustion engine

The requirement to remove impurities in biogas varies and it depends on the specification of the ultimate use of such fuel gas. The sulphur content in hydrogen sulphide causes sulphur stress cracking (SSC) which leads to corrosion of metal surface. During the process, sulphides of iron and hydrogen are formed. The SSC process is initialised on metal surface at H_2S concentration greater than 50 ppm. H_2S concentration in biogas exceeding 3,500 ppm, leads to corrosion on the interior of ICE. Approximately 10-15% of ICE life span is lost due to the presence of H_2S in fuel. When high N_2 content fuel is used in vehicles, the catalytic converters in the exhaust system breaks down N_2 gases to produce NO_x which is potent GHG and react with moisture to form acidic gases.

The presence of CO_2 in biogas is undesirable because it lowers the power output from the engine, limits its utility to only low energy applications, occupies additional space in the storage cylinders, causes freezing at valves and metering points, and lowers the thermal efficiency of the engine. Table 7-4 gives a summary of the effect of impurities in biogas on ICE if they exceed a specified limit.

Table 7-4 Effect of biogas impurities on ICE

Component	Content	Effect
CO_2	25-30%	• Reduces heating value • Increases CH_4 number and anti-knock properties of ICE • Causes corrosion when mixed with vapour • Damage alkali fuel
H_2S	0-0.5% by vol.	• Corrode equipment and piping system, a maximum of 0.05% by vol. is allowed by most OEM. • Complete combustion emits SO_2 while incomplete combustion emits H_2S. Maximum emission limit for H_2S in fuels is 0.1% by vol.

		• Spoils catalyst
NH_3	0-0.05% by vol.	• Damage to fuel cell when combusted • Anti-knocked properties of engines is increased
Water (vapour)	1-5% by vol.	• Corrode equipment, piping and instrumentation systems, storage tank and engines • Condensate damages instrument and equipment • Possibility of freezing in piping system and nozzles due to high pressure
Dust	>5 µm	• Block nozzles and fuel cells • Damage to compressors and instrumentation systems due to clogging
N_2	0.5% by vol.	• Reduces heating value • Increases the anti-knock properties of engines
Siloxane	0-50 mg/m^3	• Has abrasive effect and damage engines • Formation of SiO_2 • Formation of deposit on valves, spark plugs and cylinder heads
HC's, Cl^-, F^-	trace	• Corrosion in combustion engine

7.4 Biomethane Production

Upgrading biogas to biomethane involves two major steps, namely cleaning and CH_4 enrichment. To some extent, many of the techniques used for removing CO_2 during enrichment can also remove other acid gases and impurities from biogas. Nevertheless, it is often recommended that biogas be cleaned before the enrichment process, since these acidic gases can cause operational problems in the upgrading plant, increase maintenance cost, reduce equipment efficiencies and life span. The cost of cleaning is dependent on the composition and volume of the biogas to be treated but generally it is in the range of 30-100% of the CH_4 enrichment process capital cost. Hence, it is necessary to briefly examine the cleaning of biogas separately, after which upgrading techniques will be discussed in detail. Table 7-, Table 7-, and Table 7- summarises advantages and disadvantages of various techniques to remove H_2S, siloxane and water vapour respectively.

Table 7-5 Advantages and disadvantages of various techniques to remove H_2S

Method	Advantages	Disadvantages
Biological process with O_2/air (in filter/scrubber/ digester)	• Low investment cost • Low energy requirement • Chemicals and specialised equipment not required • Simple to operate and maintain	• Concentration of H_2S still high (100-300 cm^3/m^3) • Excess O_2/N_2 in the product will require another cleaning process • Explosion is possible if air concentration is not controlled
$FeCl_3/FeCl_2/FeSO_4$ (in digester)	• Low investment cost • Low energy requirement • Simple to operate and maintain • Compact technique • No air in biogas	• Low efficiency (100-150 cm^3/m^3) • Use of iron salt makes the operation expensive • pH/temperature fluctuation alters biogas digestion process • Dossing accuracy is difficult to maintain
$Fe_2O_3/Fe(OH)_3$-bed	• >99% removal efficiency • Mercaptan is also captured • Cheap investment • Simple process	• Sensitivity for water • Expensive operation costs • High risk of chip ignition since reaction is exotherm • Reaction surface reduced each cycle • Toxic dust is emitted
Adsorption on activated carbon (impregnated with KI 1-5%)	• High efficiency (H_2S<3 cm^3/m^3) • Excellent purification rate • Low operation temperature • Compact technique • High loading capacity	• High initial investment and operating cost • CH_4 losses • Water and O_2 needed to remove H_2S • Reduced efficiency if water is present in the biogas • Regeneration at 450 °C • Residue present till 850 °C
Absorption in water	• H_2S<15 cm^3/m^3 • Cheap if water can be easily sourced	• Expensive operation: high pressure, low temperature • Difficult technique

	• Simultaneous removal of CO_2	• Clogging of the absorption column possible
Chemical absorption NaOH $FeCl_3$	• Low energy required • Scaled down size for process equipment as compared to physical absorption for same feed volume • More efficient that physical absorption	• Expensive investment and operation • More difficult technique • Not regenerative
Chemical absorption $Fe(OH)_3$ Fe-EDTA Cooab™	• Highly efficient (~95-100%) • Cheap operation • Small volume solvent required as compared to physical absorption • Regenerative • Low CH_4 losses	• Difficult technique • Regeneration through oxygenation • CO_2 to H_2CO_3 (using EDTA) leads to precipitation • Thiosulphate is easily build-up from chelates $+H_2S$
Membranes	• >98% efficiency is achievable • Simultaneous removal of CO_2	• Expensive operation and maintenance • Complex
Biological filter	• >97% efficiency is achievable • Operation cost is low	• Post treatment process is required to reach vehicular fuel quality • O_2/N_2 in the product will require additional cleaning process

Table 7-6 Advantages and disadvantages of various techniques to remove siloxanes

Method	Advantages	Disadvantages
Absorption with organic solvents	• Approximately 97% removal efficiency	• Complete removal not possible • Corrosion
Absorption in strong acid	• Highly efficient but <95%	• Environmental issues • Hazardous chemicals
Absorption in strong base	• n.d*	• Corrosion • CO_3^{2-} precipitation • Hazardous chemical

Adsorption on silica gel	• Highly efficient but <95% • 50% more efficient as compared to activated carbon • It can be regenerated with 95% desorption efficiency at 250 °C	• Requires high operating pressure • Efficiency is reduced if moisture is present in the biogas
Adsorption on activated carbon	• Approximately 95% efficient • It can be regenerated, though the rate of desorption is less than what is obtainable with silica gel	• Increased adsorption capacity requires increased pressure • Efficiency is reduced if moisture is present in the biogas
Cryogenic separation	• Approximately 99% efficient process at -70 °C • Removal of several impurities	• High investment and operating cost • It requires specialised equipment for high pressure and very low temperature operation

*not used due to CO_3^{2-} precipitation

Table 7-7 Advantages and disadvantage of various techniques to remove water vapour

Methods	Advantages	Disadvantages
Condensation method • Demister • Cyclone • Moisture trap	• Highly efficient for removal of hydrocarbon dust and oil. • Simple technique • Often used as pre-treatment before other technique	• Atmospheric: dew point minimum 1 °C • High probability of freezing
Adsorption • Silica • Activated alumina	• Highly efficient with dew point of -10 till -20 °C • Low operational cost • Regeneration possible	• High investment cost with feed pressure of 6-10 bar • Requires another process for removal of dust and oil
Absorption with glycol	• Highly efficient with dew point of -5 till -15 °C • Highly efficient for removal of hydrocarbon dust and oil.	• High investment cost • Requires high pressure and temperature of 200 °C for regeneration

	• Not toxic or dangerous	• Higher gas volume (>500 m^3/hr) to be economical
Absorption with hygroscopic salt	• High removal efficiency • Not toxic or dangerous	• No regeneration done for hygroscopic salt

Aside the three major impurities mentioned above, ammonia, air and other trace impurities should be removed or reduced if they exceed the threshold limit specified for fuel by either the original equipment manufacturer or the environmental legislation.

7.5 CH_4 enrichment

The enrichment process is mainly to separate the non-cumbistible CO2 in the biogas after other trace impurities have been removed to produce biomethane. The main purpose of upgrading biogas produced from the organic wastes collected from Robinson Deep Landfill and Joburg Market is to produce biomethane of high quality (>95% CH_4) which could be used to fuel CoJ metro buses. There are various techniques that could be set up in order to achieve the upgrade of biogas to biomethane such as: absorption, adsorption, membrane and cryogenic technique. Nevertheless, the choice of a chosen technique depends largely on some important factors such as (i) Biogas composition, (ii) Available resources (water, electricity and space) (iii) Target purity of CH_4. (iv) Environmental issues regarding the disposal of hazardous waste. (v) Volume of biogas to be upgraded.

7.5.1 Absorption

Absorption is a diffusional operation in which some components of biogas in the gas phase are absorbed by the liquid they are in contact with. The region separating the two phases is called the interfacial region. Absorption is reported as the most widely used separation process. This separation principle is critically based on the solubility of the solute (biogas impurities) in the solvent. There are two types of absorption processes which are determined by the reaction between the solute and solvent. They are physical absorption and chemical absorption processes. The benefits and operational challenges associated with absorption technique is presented in Table 7-2.

7.5.1.1 Physical Absorption Process

Physical absorption process depends on the degree of solubility of the solute in the solvent without any chemical reaction. Pressurised gas scrubbing using water as the absorbent is a physical absorption process. Other solvents used in the process are polyethylene glycol-dimethyl ether (PEG-DME), examples of which is genosorb 1753 solvent, otherwise known as selexol, and propylene carbonate which are both organic solvents. Figure 7-2 shows a schematic illustration of a water scrubber.

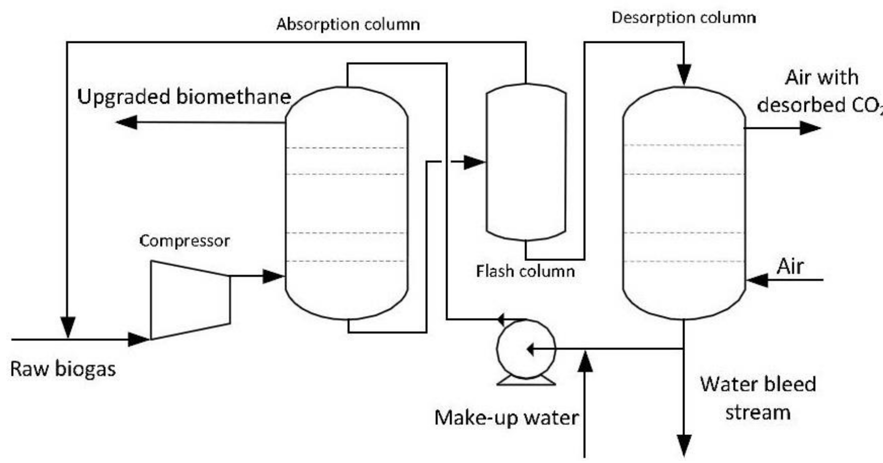


Figure 7-2 Water scrubbing process flow diagram

Compared to water, organic solvents are more efficient in absorbing CO_2 and can be operated at low pressure with good chemical stability. They are however, more corrosive. The theoretical background for absorption in organic solvent is similar as to that of water scrubber. However, the solubility of CO_2 is much higher in the organic solvent than in water. CO_2 has a solubility of 0.18 M/atm in polyethelene glycol-dimethyl ether which is about five times higher than in water, thus, for the same upgrading capacity the overall scrubber design size and volume of solvent is less when compared to using water.

7.5.1.2 Chemical absorption

Chemical absorption process is based on the reactivity of the chemical reagent used as absorbent to chemically react with CO_2 molecule and thus removing it from the biogas feed stream. It has an advantage over physical scrubbing in its capacity to absorb more CO_2. Chemical absorption is generally performed using amines solutions and alkaline reagents. The common types of amine compounds used are mono-ethanolamine (MEA), di-methyl ethanolamine (MDEA), di-ethanol amine (DEA), deglycol amine (DGA) and diisopropanol amine (DIPA). The reaction of CO_2 with amine is slow as compared to H_2S which is instantaneous, however, effective absorption of H_2S and CO_2 in a packed column using amine is aided by adequate mechanical diffusion incorporated into the system as well as increasing the gas/liquid contact area.

Table 7-2 Benefits and operational challenges associated with absorption

Benefits	Operational challenges
• Physical absorption requires less material. • Effective simultaneous removal of H_2S and	• Alkali aqueous solutions are not re-generable, therefore large volume of the solvent is required.

NH_3 is achievable in amine absorbent. • Biomethane stream produced by the process can be directly utilised at delivery pressure but must be compressed for use as vehicular fuel. • Complete CO_2 removal using amine is achievable. • The process is highly efficient at optimal operating condition. • It is a proven technology. • Off-gas treatment used to augment the heat demand of the plant. • Amine scrubbers can operate at very low pressure when compared to water scrubber.	• Alkanolamines are re-generable but at high temperature with loss of amine after regeneration. • Fluctuation in efficiency of the absorbent due to refilling of lost amine and dilution of glycol with water. • Corrosion of scrubbing column, pump, pipe and compressor caused by the reaction of water and H_2S which reduces the operational life of the plant. • Clogging by microbal growth and conversion of H_2S to elemental sulphur will reduce the efficiency of the scrubber over a period of time. • Foaming can also occur when the flow rate of absorbent is not properly regulated. • Disposal problems of contaminated water. • Organic solvent requires heating system and a cooling system for regeneration. • High temperature requirement. • Low flexibility towards variation of input gas for water scrubbers.

7.5.2 Adsorption

Adsorption is the selective concentration of one or more components of a gas at the surface of a micro-porous solid, preferably one with a large surface area per unit mass. The mixture of the adsorbed components in this case, raw biogas, is called the adsorbate and the micro-porous solid is the adsorbent. Figure 7-3 shows a typical adsorption process of biogas impurities over a micro-porous solid surface. The benefits and operational challenges of adsorption techniques is presented in Table 7-3.

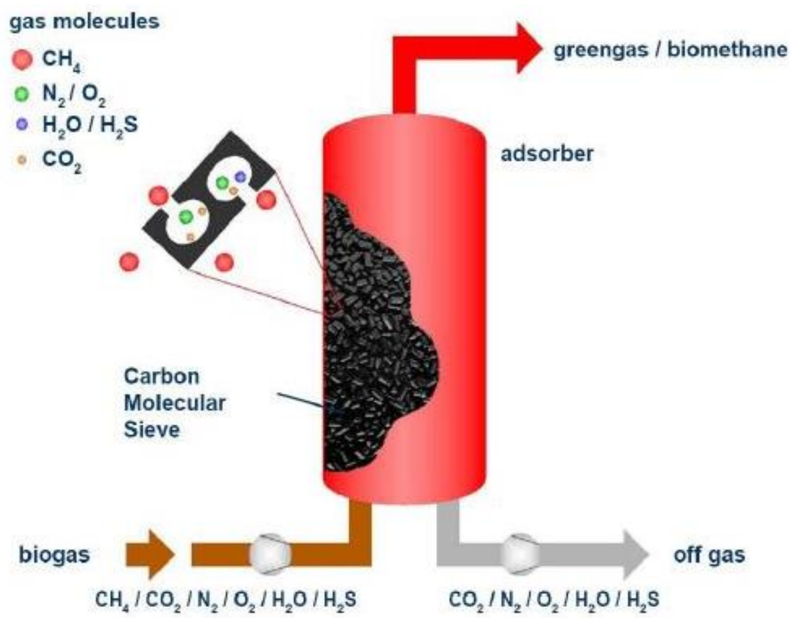


Figure 7-3 Adsorption of biogas impurities over carbon molecular sieve

Pressure swing adsorption (PSA) and temperature swing adsorption (TSA) are two types of adsorption processes. Of importance is the PSA, a dry method to separate gases via their physical properties differences at elevated pressure. When the total pressure of a system "swings" between high pressure in feed and low pressure in regeneration, the process is termed PSA. For continuous upgrading process using PSA, several columns are required and connected to use the output of one vessel as the feed of the other. The molecular size of CH_4 and CO_2 are 3.8 Å and 3.4 Å respectively. Therefore, an adsorbent with pore matrix of 3.7 Å when selected will retain most CO_2 until it is saturated whilst CH_4 is restricted from getting into the pore but passes through interstitial spaces.

Table 7-3 Benefits and operational challenges of adsorption technique

Benefits	Operational challenges
• The process of PSA requires less heat. • There is flexibility of design and more than one absorbent can be used in the process. • It is suitable for small to medium scale plants. • PSA technology is a dry process with no contaminated liquid waste. • No bacteria contaminant of off-gas. • Highly efficient with 95-98% CH_4 recovery.	• High energy consumption. • Operates at high pressure, hence requires a cooling system for compressor. • Requires a separate system for removal of H_2S to extend efficiency and adsorbent life. • Expensive process control is required to regulate the different cycles. • CH_4 losses are high when valves malfunctions.

7.5.3 Membrane

Membranes are discrete, thin semi-permeable barriers that selectively separate a feed mixture containing two or more species from one another. The species that moves through the barrier is called permeate and the rejected specie is called retentate. Gases can be separated on two types of membranes; dense membrane (non-porous) and porous membrane. The transportation of gases through dense membranes occur via solution diffusion while for porous membranes; Knudsen flow, selective adsorption/diffusion and molecular sieving are the predominant processes. The transportation of gases through membranes takes place when a driving force is applied to the gas species. This driving force is mostly due to pressure difference or concentration difference across the membrane. The accurate design and optimization of a gas separation system using polymer membrane depends on the possibility of predicting correctly the membrane transport properties. A number of membrane materials, polymeric and inorganic, exist for CO_2/CH_4 separation. However, polymeric membranes are mostly used for industrial scale application due to their economic advantages over inorganic materials.

Three types of membrane module exist; hollow fiber modules; spiral wound modules and envelope type module. Hollow fiber is commonly used in biogas upgrading processes due its high packing density, low investment cost and operating cost. However, pre-treatment process is always required when hollow fiber is used because it is very susceptible to fouling by H_2S and it is difficult to clean. Figure 7-4 shows a schematic diagram of a hollow fiber membrane [109].

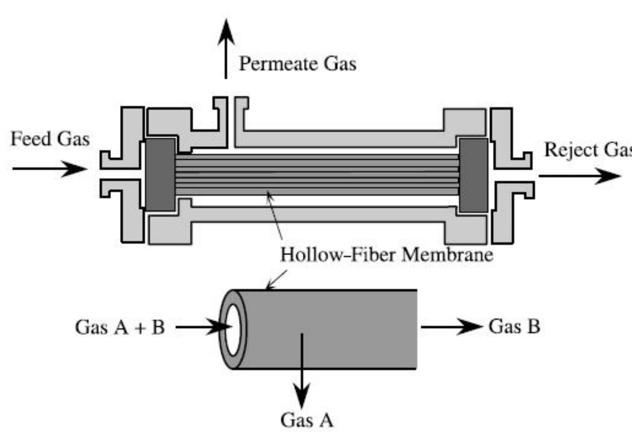


Figure 7-4 Schematic diagram of a hollow fiber membrane module

Membrane module configuration and permeate flow pattern have significant effect of the upgrading process aside the effect of selectivity, pressure ratio and stage cut. Due to imperfect separation, a cascade configuration is required. The cascade arrangement of modules for separation to achieve a desired product purity and recovery of feed specie is called stage(s). This arrangement is based on economic considerations and the end-use of the product. On economic consideration, three important elements are considered; the cost of membrane plant (membrane element and pressure housing); the capital and operating cost; and product losses. The quality of the product depends on the end use. Critical operating parameters that affects the quality of upgraded biogas and CH_4 recovery in hollow fiber membranes are the feed composition, pressure and feed flow rate which is a function of the plant capacity.

Table 7-4 Benefit and operational challenges of membrane technique

Benefits	Operational challenges
• Lower capital cost as compared to other upgrading technique except water scrubbing. • Operational simplicity and high reliability on upgrade biogas. • Space optimization and compactness of the design. • Environmentally friendly technique as there is no waste solvent, permeate gas can be flared or used as fuel for heat engines. • The technique is ideal for remote location once designed and install. • Absence of moving parts leads to low level mechanical wear. • Low maintenance level.	• Blockage of membrane surface area when exposed to particles. • Plasticization of the membrane material when used for H_2S separation. • Low resistance to breakage under high pressure. • Efficiency reduces over time, hence, requires replacement. • Little operational experience with the technology on biogas separation.

7.5.4 Cryogenic

Cryogenic separation uses the different temperature related properties of the gas species to separate them from the gas mixture. The process starts with compression of raw biogas to 26 bar and then cooled to -26 °C for removal of H_2S, SO_2, halogens and siloxane. The raw biogas is cooled down step-wisely to temperature where CO_2 in the gas can be liquefied and separated through several heat exchangers. The compressed biogas is dried in advance to prevent freezing. Pure CO_2 has a desublimation temperature of

-78.5 °C at atmospheric pressure while CH_4 condenses at -161 °C. Depending on the temperature of the process different purity can be reached. The lower the temperature, the higher the product purity. However, the presence of CH_4 in the biogas mixture affects the physical properties of the gas thus requiring higher pressure and\or much lower temperature to condense CO_2. The two main working process cycles of cooling systems as used in the cryogenic biogas upgrading are open loop process cycle and the closed loop process cycle. In the open loop process cycle biogas is first compressed to a high pressure causing a rise in temperature. This creates a good physical property for the biogas to be heat exchanged with lower temperature heat sink. After the biogas has been cooled, it is expanded through a turbine. The biogas can this way reach a low enough temperature to begin the desublimation of CO_2. In the closed loop process cycle, biogas is not compressed before been heat exchanged thus resulting in temperature difference between the biogas stream and the heat exchanger medium. Since the biogas temperature is not increased via compression, it is not possible to use air as a heat sink therefore a cooling agent mostly N_2 is required to cool the biogas before expansion in a turbine. This decreases both the pressure and temperature which leads to the sublimation of CO_2. This technique has not been implemented at an industrial scale yet. The benefits and operational challenges limiting the technology is presented in Table 7-5

Table 7-5 Benefits and operational challenges of cryogenic technique

Benefits	Operational challenges
• Lower capital cost as compared to other upgrading technique except water scrubbing. • Operational simplicity and high reliability on upgrade biogas. • Space optimization and compactness of the design. • Environmentally friendly technique as there is no waste solvent, permeate gas can be flared or used as fuel for heat engines. • The technique is ideal for remote location once designed and install. • Absence of moving parts leads to low level	• High pressure and low temperature is required for this process. • The electricity demand ranges from 0.68-1.8 kWh electricity per Nm^3 of biogas for upgrading which is not energy efficient. • The frost layer produced by CO_2 reduces the heat exchange efficiency. • High investment and operation cost.

mechanical wear. • Low maintenance level.

7.6 Conversion of vehicle to use biomethane

Three types of NGVs are available, they are; dedicated NGVs which are designed to use natural gas only; bi-fuel NGVs which are designed to either run on natural gas or gasoline alternatively; and dual fuel NGVs which run on blended fuel of natural gas and diesel by injecting the blend into a turbocharger. Biomethane can be used as substitute to natural gas without any further alteration of the NGV. During cold start of NGVs, gasoline and diesel are the fuels used for ignition in both bi-fuel and dual fuel NGVs respectively. Once the normal operating temperature is attained, the system automatically switches to biomethane or the blended fuel. Reduced efficiency and low output power are associated with bi-fuel engine when operating on natural gas/biomethane but when it switches to gasoline, the efficiency and power output increases. However, dedicated NGV engines have higher efficiency to a level similar to that of gasoline engine due to the high octane rating of natural gas and the purpose built engine optimized for the fuel only. Table 7-6 shows the advantages and disadvantages of the three NGV. Figure 7-5 show a complete kit for bi-fuel NGV. The kit presented in Figure 7-5 can also be used for biomethane without any further alteration of the system. The conversion kits consist of fuel storage cylinders and bracket, fuel lines, regulator, a fuel-air mixer, pressure reducer and a switch that allows the driver to alternate between gasoline and CBG manually. The cost of converting gasoline vehicles which were not originally designed to operate as bi-fuel varies. The cost depends on the engine size, vehicle make and model, the size and number of the pressurised cylindrical tanks, number of cylinder in the engine and also if customisation of a part is required. The conversion cost ranges between \$2,700 to \$5,500 for 4-8 cylinder engine in medium size car and vans. While the conversion cost for heavy duty truck ranges between \$5,300 to \$10,600. In the international market, the cost of light duty OEM NGVs is higher than gasoline vehicle in the range of \$1,900 to \$4,500 depending on the national tax regime for new vehicle while price increase for medium duty commercial vehicle ranges from \$6,500 to \$9,000 depending on the type of vehicle and its application. For heavy duty vehicle, the price has been reported to be higher by 20-25% the cost of its diesel engine equivalent.

Table 7-6 Comparison of advantages and disadvantages of bi-fuel/dual fuel and dedicated fuel system

Bi-fuel/Dual fuel system	Dedicated fuel system
Advantages	Advantages
• Cost of retrofitting is low	• Optimal engine performance with higher power output, lower fuel consumption, better exhaust gas emission
• Independent of fuelling infrastructure deficiency	• Secured use of CNG infrastructure
• Higher total distance travel range due to two different fuel system	• Optimised design to accommodate more CNG tanks
• Fuel efficiency at par with gasoline	• Negligible emission of particulate matter
• Less CNG tank compared to dedicated result in less weight added to vehicle	• Better access to incentive program
Disadvantages	Disadvantages
• Compromise on engine technology	• High cost of engine development
• Restricted range of operation when operating only on natural gas	• Restricted total driving range depending of fuelling station availability
• Fuel cost is higher when operating frequently on diesel mode	• Maintenance knowledge still low

Figure 7-5 Complete natural gas kit for vehicle integration

7.7 Life Cycle cost of using biomethane as vehicle fuel

The life cycle analysis (LCA) of cost, energy demand and GHG emissions are important component in assessing deployment of any vehicle fuel. LCA of vehicle fuel include their extraction, processing, transport, utilisation and emissions. A well-to-well (WTW) analysis describe a complete cycle for vehicle fuel. The WTW is of two stages namely; well-to-tank (WTT) which is the upstream part and covers the production of the fuel including extraction, transportation, distribution and its storage on board a vehicle while tank-to-wheel (TTW) which is the downstream part, covers the end use of the product (combustion) and exhaust emissions. The GHG savings achieved in the production and utilisation of biomethane varies considerably but generally, it depend on digested substrate, substrate transport distance, chosen digestion technique, production capacity, upgrading technique and end use equipment efficiency. Biomethane produced from municipal waste and animal manure has been reported to achieve GHG savings approximately 50% and 80% respectively when compared to conventional fossil fuel. Using biomethane as fuel for vehicle, a lifecycle CO_2 reduction of 49-63% has been reported. Overall, biomethane has the lowest carbon intensity of road transport fuels, a significant reduction in air pollutants and lower noise emission during vehicle operation.

7.8 Economic Consideration for biomethane production

The economic assessment performance of any given configuration of separation processes varies and depends very much on the assumptions used in the assessment. Economic considerations include information on total investment cost, annual variable operating and maintenance cost, annual cost of CH_4 lost in the plant and annual capital related cost. All these costs are estimated to determine the gas processing cost (GPC). The GPC is the total cost incurred to produce a cubic meter of biomethane. The GPC is influenced by the scale of the plant, technology adopted, location and operating process conditions. Severn Wye Energy Agency (SWEA) reported an average investment cost for a biogas plant though the details of the equipment, feed flow, feed composition and product purity was not specified. According to SWEA data, the investment cost of membrane installation for biogas plant of 100 m^3/h of biomethane is in the range of €7,300 to €7,600/(m^3 biomethane/h). For the same capacity of the installation with water scrubbing equipment, the price is €10,100/(m^3 biomethane/h) and €10,400/(m^3 biomethane/h) for biogas plant with PSA. As the volume of produced biomethane increases to 500 m^3/h, the investment cost reduces to about €3,500/(m^3 biomethane/h). Other published work reported GPC to decrease as the volume of feed biogas increases but generally, GPC is roughly in the range of \$0.1 to \$0.7/m^3 of biomethane. A detailed economic report by de Hullu (2008) considering different techniques for a biogas upgrading plant is presented in Table 7-7. The fixed assumptions are feed flow 250 Nm^3/h with 60% CH_4, electricity cost was €0.10/kWh, water cost €0.92/m^3 and service cost was €50,000/year.

Table 7-7 Biogas upgrading technique cost comparison

Technique	water scrubbing	Chem. Absorption	PSA	Membrane	Cryogenic
Total investment cost (€)	265,000	869,000	680,000	749,000	908,500
Total running cost (€)	10,000	179,500	187,250	126,750	397,500
Gas processing cost (€/Nm^3)	0.13	0.28	0.25	0.22	0.44
Gas processing cost ($/$Nm^3$)	0.16	0.35	0.31	0.27	0.55
Product flow rate (Nm^3)	144	137	139	130	161
CH_4 recovery (%)	94	90	91	78	98
Product purity (%)	98	98	98	89.5	91
Waste Stream (%CH_4 Conc.)	2(6)	2(10)	1(9)	1(22)	1(2)

Considering the GPC, water scrubbing is the cheapest which can be directly related to the least investment cost of the four techniques. Cryogenic separation had the highest investment cost hence the highest GPC. The investment cost of PSA is quite high but the GPC is at an average compared to the other four techniques. The biggest difference in the investment cost resides in the equipment required and the cost of manufacturing. Membrane GPC was high at €0.22/Nm^3 of biomethane due to the 22% CH_4 loss while processing cost was also included in its GPC. The higher CH_4 losses generated by membrane systems increased the biogas processing cost. However, the CH_4 lost during the upgrading process of biogas obtained from anaerobic digesters, could be used as fuel for heat generation since anaerobic digestion typically requires higher than ambient temperature for optimal operation.

The energy requirement of the upgrading process is also a factor to be considered in technology adoption. Physical absorption, adsorption, membrane and cryogenic upgrading techniques are highly dependent on electricity. Table 7-8summarises the electricity and energy requirement of four upgrading techniques. The heating value for biomethane (100% CH_4 concentration) is approximately 35 MJ which is equivalent to 9.7 kWh. This was used to estimate the energy required for upgrading in column 4 of Table 7-8.

Table 7-8 Electricity and energy demand of the upgrading techniques

Separation technique	Electricity demand (kWh/m^3 biomethane)	Heat demand (kWh/m^3 biomethane)	Upgrading energy/ CH_4 heating value (%)
Physical absorption (water)	0.2-0.3, 0.4-0.5	None	2.1-3.1, 4.1-5.2
Physical absorption (organic)	0.10-0.15, 0.23-0.33	None	1-1.5, 2.4-3.4
Chemical absorption (amines)	0.06-0.17, 0.05-0.18	0.2-0.4	0.6-1.8, 0.5-1.9
Adsorption (PSA)	0.16-0.35, 0.29-0.60	None	1.6-3.6, 3-6.2
Membrane	0.18-0.35, 0.26, 0.20-0.30	None	1.9-3.6, 2.7, 2.1-3.1
Cryogenic separation	0.18-0.25, 0.42-0.63	None	1.9-2.6, 4.3-6.5

From Table 7-8, chemical absorption upgrading energy demand is the least of the four techniques and demand ranges between 0.6-1.9% of CH_4 heating value but requires heat as high as 120 °C for regeneration when MEA is used as absorbent. Generally, absorption processes is best operated at low temperature and high pressure while desorption process requires an increased temperature hence a heating and cooling system is required. Cryogenic requires the highest demand on electricity which ranges between 1.9-6.5% of CH_4 heating value for the upgrading process. The energy requirement of a cryogenic plant is reported to be about 580.9 kJ/m^3 of biomethane with a heat pump cycle operating between -100 °C to 40 °C. Adsorption technique was also high because of the compression energy required but membrane technique was about the average of all the processes. The energy demand ranges between 1.9-3.1% of CH_4 heating value.

7.9 MCDA for selecting the upgrading technique

AHP has been applied to select the most suitable upgrading technology based on environmental sustainability as the main goal. Four criteria were considered namely environmental, product purity, economics and energy demand, and ease of use and adaptability to CoJ. The weight of each criterion against the desired goal is as presented in Table 7-9.

Table 7-9 Weight of criteria for alternative pair wise comparison

	Environmental	Product purity	Economics and energy demand	Ease of use and adaptability
Weighted Factors	41%	38%	10%	11%

Four alternative technologies were research upon to evaluate their performance characteristics against each criterion. The priority vector of each alternative technology against each criterion were calculated and presented in Table 7-10 and Figure 7-6

Table 7-10 Overall priority vector of alternatives against criteria

	Environmental	Product purity	Economics	Ease of Tech	**Overall Priority**	**Idealized Priority**
Absorption	0.08	0.13	0.04	0.02	26.9%	99%
Adsorption	0.12	0.09	0.02	0.02	25.3%	93%
Membrane	0.10	0.08	0.03	0.06	27.2%	100%
Cryogenic	0.11	0.09	0.005	0.005	20.6%	76%

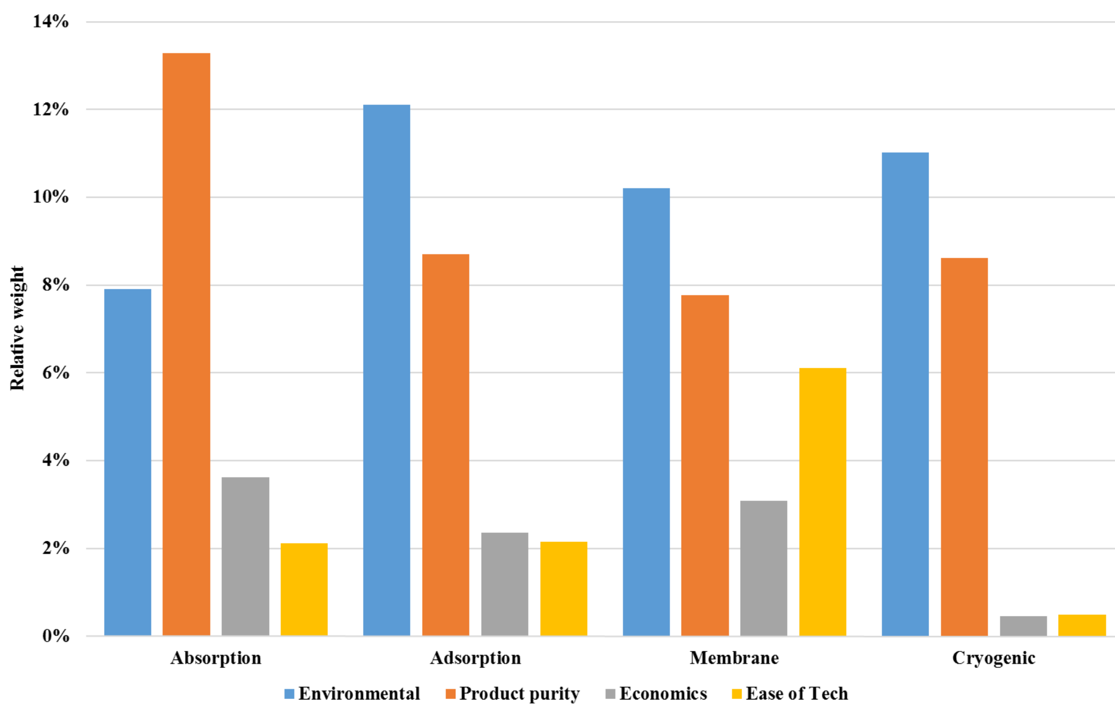


Figure 7-6 Ranking of technology performance against each criterion

Of the four alternatives investigated, membrane technology is most preferred in satisfying the main goal alongside it adaptability to the Johannesburg environmental conditions and technical know-how as shown in Figure 7-7. Two alternative technologies that are also competitive with membrane are absorption with 99% preference to membrane and adsorption with 93% preference to membrane as shown in Table 7-10 at this scale of plant. At other locations with abundant water supply, absorption will be preferred over adsorption but if high standard for waste effluent and lack of water then adsorption is be preferred.

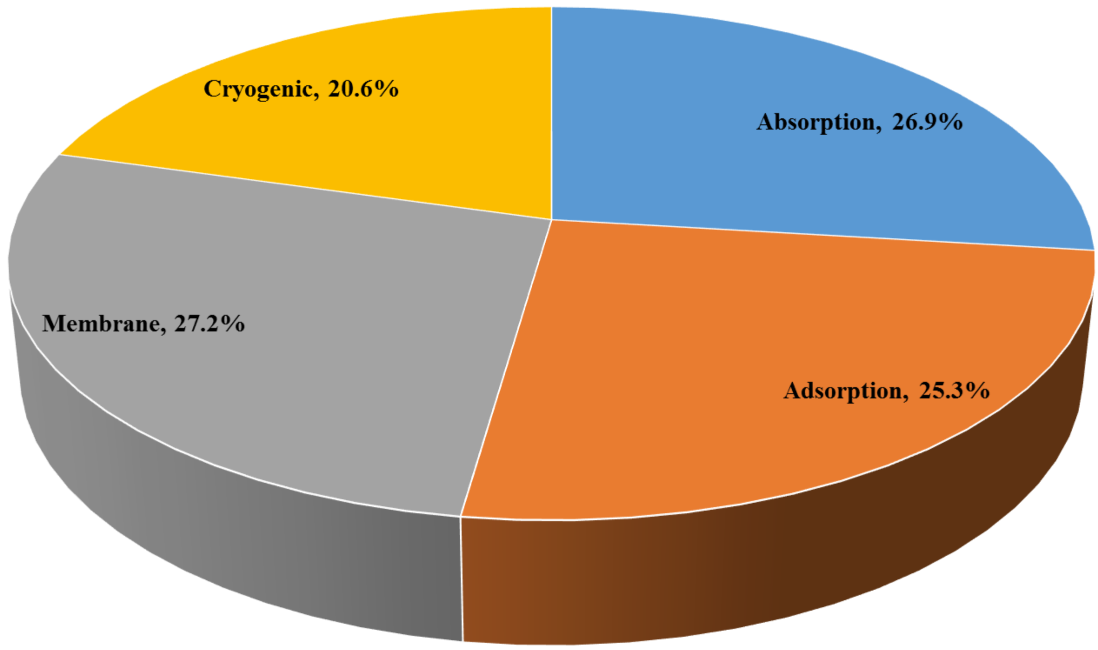


Figure 7-7 Overall technology performance towards the AHP goal

The consistency of each weight allocated to each criterion and alternatives were verified with a consistency ratio of 0.0445 as shown in Table 7-11. Consistency ratio (CR) less than 0.1 indicate that the weight allocated are acceptable and consistent.

Table 7-11 Overall consistency index and ratio of criteria weights and alternatives

Overall CI	Overall RI	Overall CR
0.0801	1.8000	0.0445

7.10 Fuel requirement of Metro Buses

The CoJ metro buses consumes approximately 50 l of diesel per 100 km according to Mr. Vusie Sithole who is the general manager of technical division of Johannesburg Metropolitan Bus Services (SOC) Limited. These buses travel on average, 200 km per day. Hence, the biomethane fuel equivalent requirement for one metro bus with 97% methane concentration will be 107 Nm^3. However, to account of engine efficiency, driving pattern and other losses, an estimated 140 Nm^3 will be required.

Based on theoretical estimate, if all organic wastes are converted into biomethane, the annual diesel equivalent will be approximately 8 million liters per year. Following a moderate estimate, considering 70% of the fuel is extracted and 140 Nm^3 of biomethane required per day, 180,959 ton of organics/ year will be sufficient to fuel 110 metro buses per year. This is about 20% of the 536 metro buses currently in service.

7.11 Digester Sizing and Plant Schematics

7.11.1 Sizing

From Table 4-7, about 327 ton of organic waste is generated per day from RCR, dailies and JM. Developing a pilot plant with the aim to fuel at least one metro bus, we have assessed the amount of waste required by first quantifying the fuel demand of a metro bus per day. As stated in section 7.10, the biogas upgrading plant should produce a minimum of 140 Nm^3 of biomethane to prove the concept of waste to energy which will require about 5 ton/day. This capacity has been double to improve its economics of scale and satisfactorily provide more than enough for a metro bus at the very worse driving condition and engine performane. Based on the waste characterization studies and preliminary BMP results presented in sections 4.8.3 and 5.2 respectively, 10 ton/day of waste will be required. Table

Table 7-12 Yield from 10 ton/day biogas plant

Parameters	Values
Total (ton/annum)	3650
Daily (ton/day)	10
TS (%)	11%
VS (%TS)	78%
Biogas yield (Nm^3/ton VS)	510
Daily biogas (Nm^3/day)	437.58
CH4 Conc.	0.58
Biomethane (Nm^3/day)	253.7964
OLR (kg VS/m^3-d)	2.86

Table 7-13 Energetic equivalent of produced biomethane and CO_2 Savings

Parameters	Values
Biogas/annum	127,773
Biomethane/annum	74,109
Annual CO_2 saved (tCO_{2eq})	1,089
Diesel eq (liter)	245
Petrol eq (liter)	271
Energy equvalent (kWh_{elec})*	834
Thermal energy (kWh)*	1,191

**CHP electrical efficiency of 35% and thermal efficiency of 50%.*

Based on a 10 ton/day feed system, consultation from both literature and academics within the University, a two stage digestion systems have been proposed. The first stage digestion (D_1) is mainly the hydrolysis stage with a hydraulic retention time of 5 days and the second stage is the main digestion (D_2) stage with 25 days' hydraulic retention time. Tab summarises the sizes of the digester. Aspect ratio of digester height to diameter of 0.4 has been used in the design. Useable volume of D_1 and D_2 are 50 m^3 and 250 m^3 respectively. Assuming a two months digestate storage, the post digestate storage volume is calculated as 308 m^3.

Table 7-14 Digester sizing parameters

Parameters	Values
Daily tonnage	10
HRT-D_1 (days)	5
HRT-D_2 (days)	25
D1 Vol (m^3)	60
D2 Vol (m^3)	300
Height-D_1 (m)	2.3
Height-D_2 (m)	3.9
Dia-D_1 (m)	5.8
Dia-D_2 (m)	9.8
Post dig. stor. (m^3)	308

Aside the main digesters, the biogas storage volume which could be in an external vessel or internal by means of membrane that covers the digester. In practice, a storage capacity of 20 to 50% for a batch upgrading process is sufficient. Depending of the frequency of upgrading, this storage volume might even be less. For this initial draft, the storage is internal via membrane. Biogas storage volume is calculated as 0.6 m3 taking a 50% storage capacity. To reduce heat losses from the digester wall, insulation is required. Table 7-15 shows the insulation dimensions calculated.

Table 7-15 Digester insulation dimensions

Parameters	Values
D_1 wall insulation (m^2)	41.93
D_2 wall insulation (m^2)	120.12
D_1 bottom insulation (m^2)	26.41
D_2 bottom insulation (m^2)	75.39

Apart from the digester which is the main component to produce the biogas, other auxiliary components such as mixer, feed pump, recycle pump, air blower to mention a few are required to effectively cost the system. However, at this stage of the study, detail material and energy balance of the whole plant including the upgrading process have not been done, hence, approximate method of costing will be applied.

7.11.2 Block Flow Diagram of the Plant

The block flow diagram from waste delivery to production of biogas is presented in Figure 7-8. While Figure 7-9 present biogas upgrading to biomethane and compression to 220 bar. The permeate during the stage one upgrading process will contain higher percentage of CO_2 and less CH_4, rather than emit to the atmosphere, a higher concentration of biomethane from stage will be mixed the stage one permeate and sent to burner to produce heat for the digesters.

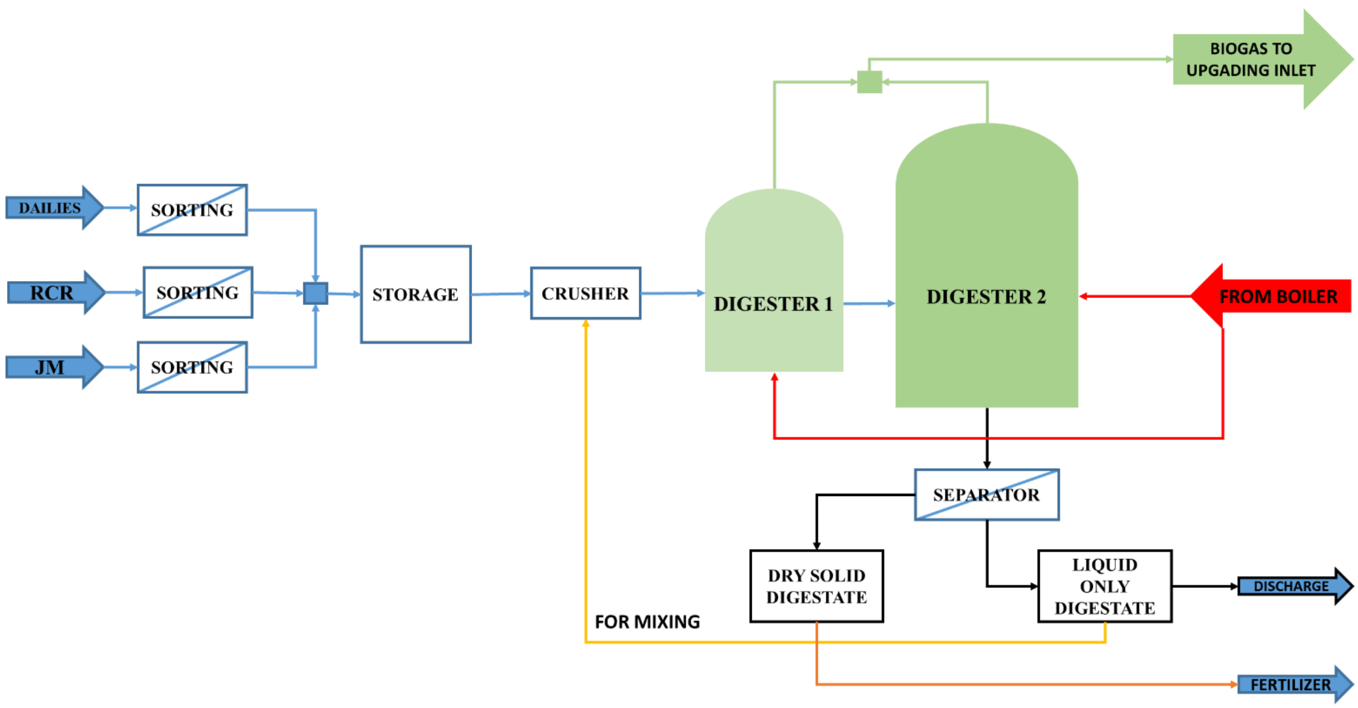


Figure 7-8 Biogas production block flow diagram

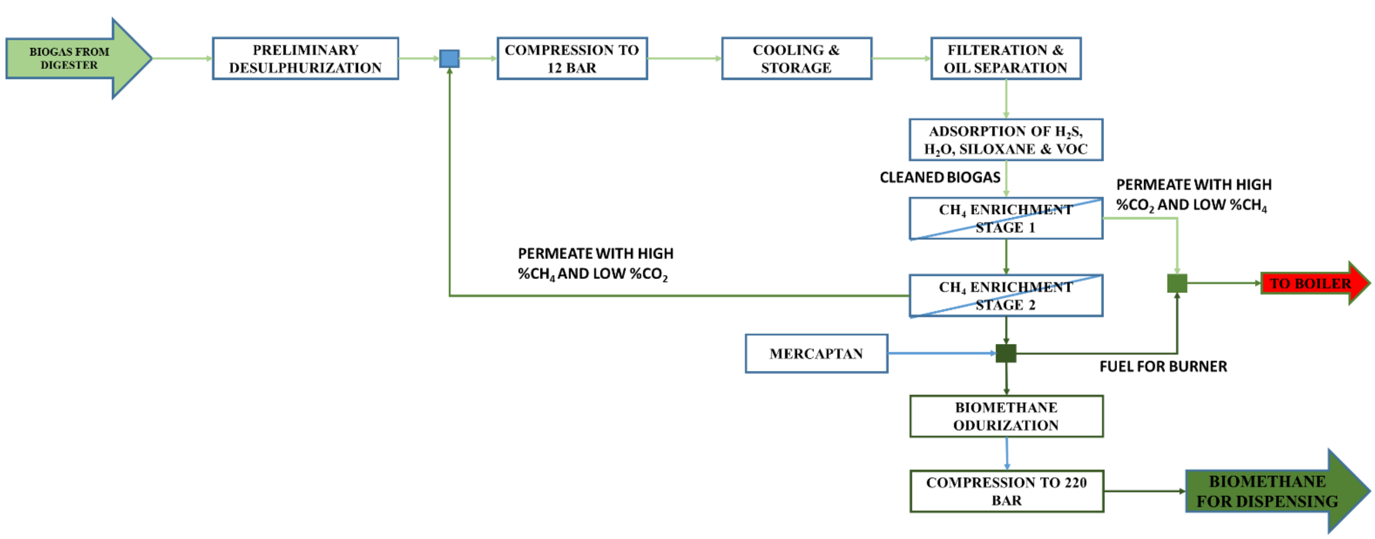


Figure 7-9 Biogas upgrading using membrane technology block flow diagram

7.11.3 Schematics

Below are figures of draft plant design drawings. A full detailed design and costing will be conducted as specified as Output 3 of the SLA.

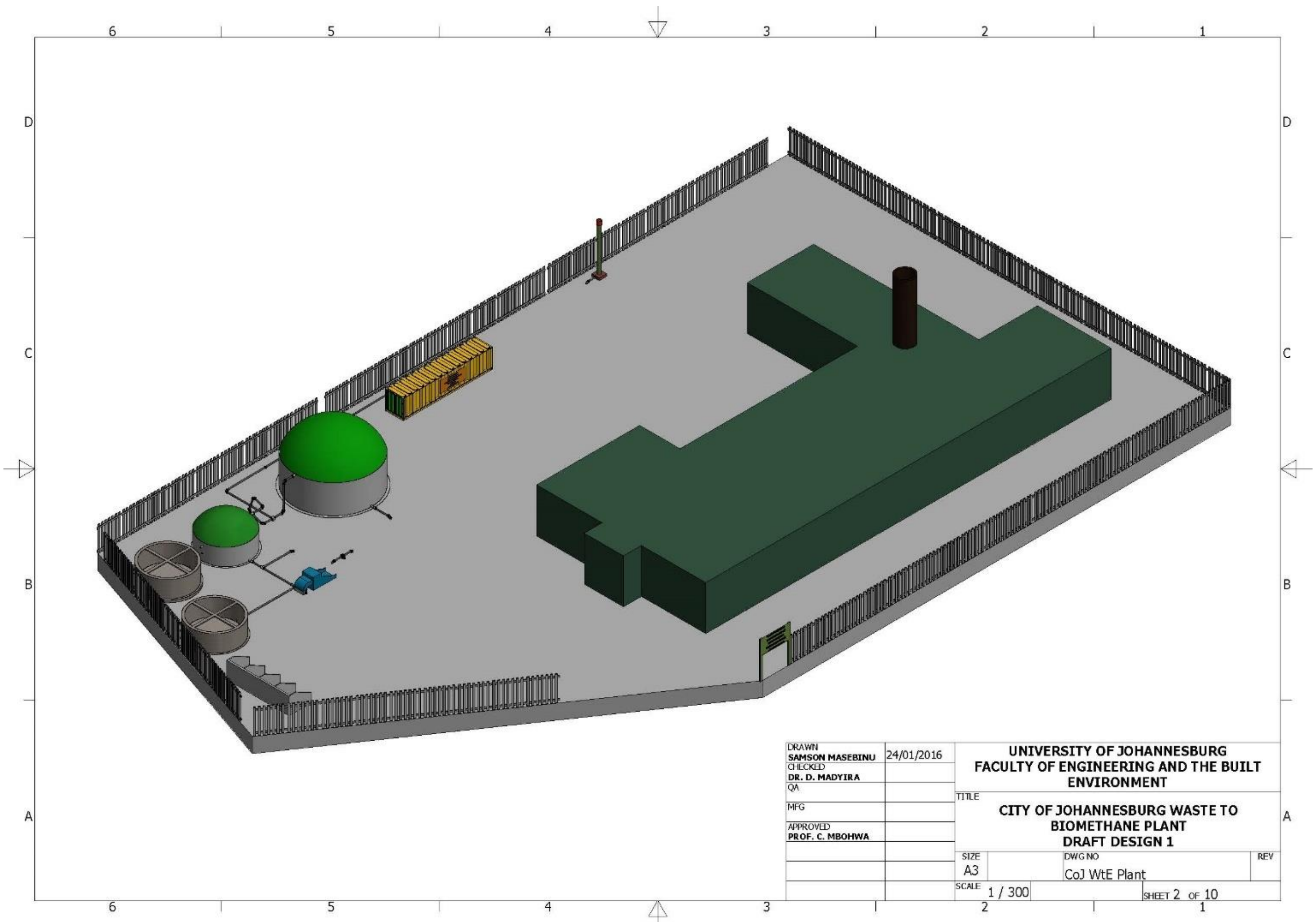


Figure 7-10 Isometric projection of the plant schematics

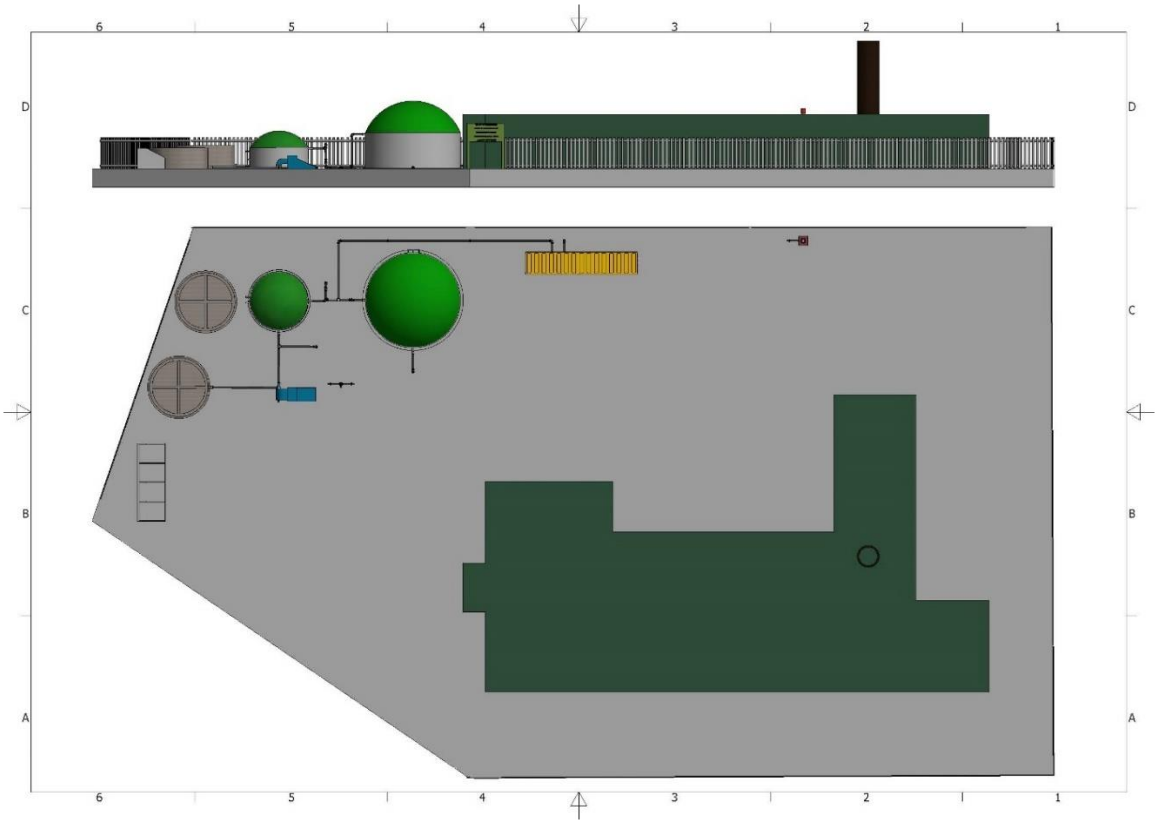


Figure 7-11 Plan view of the plant schematics

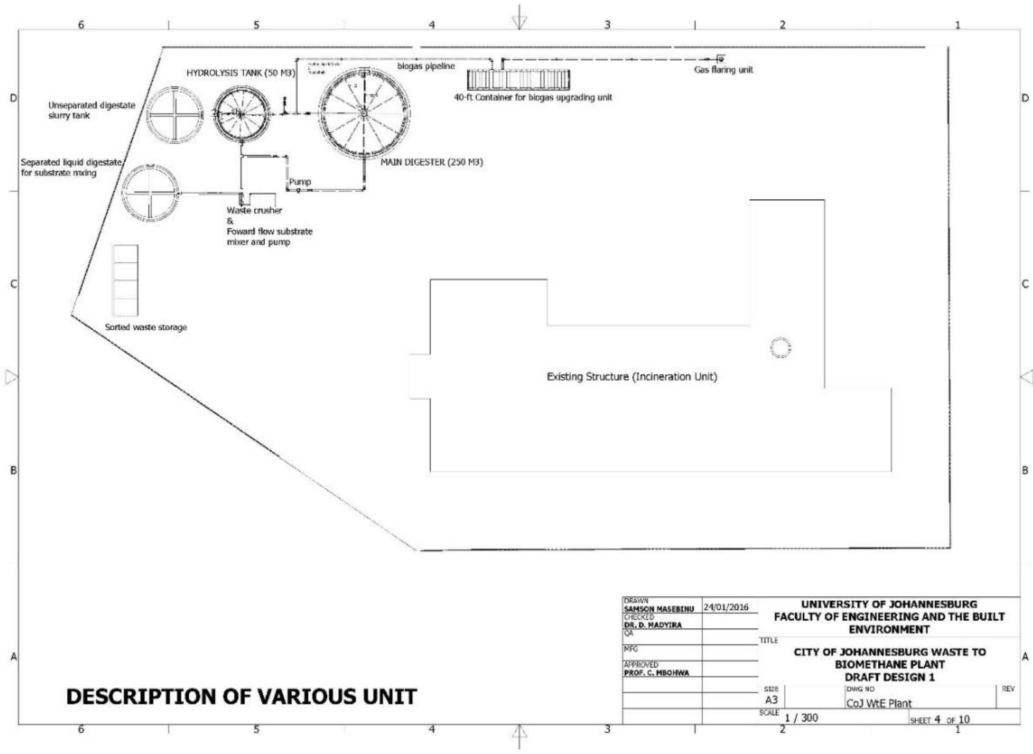


Figure 7-12 Plan view showing hidden details of plant and description of units

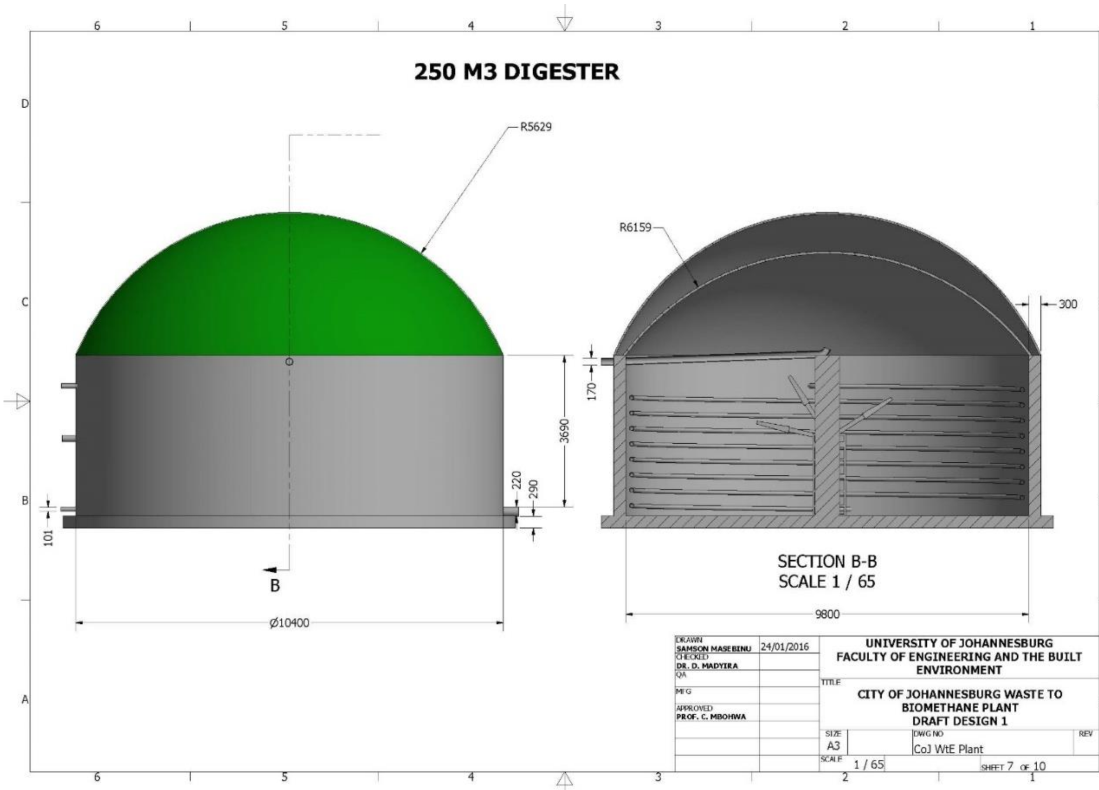


Figure 7-13 300 m³ Digester with 250 m³ useable volume. Section B-B shows internal elements of heating, agitators

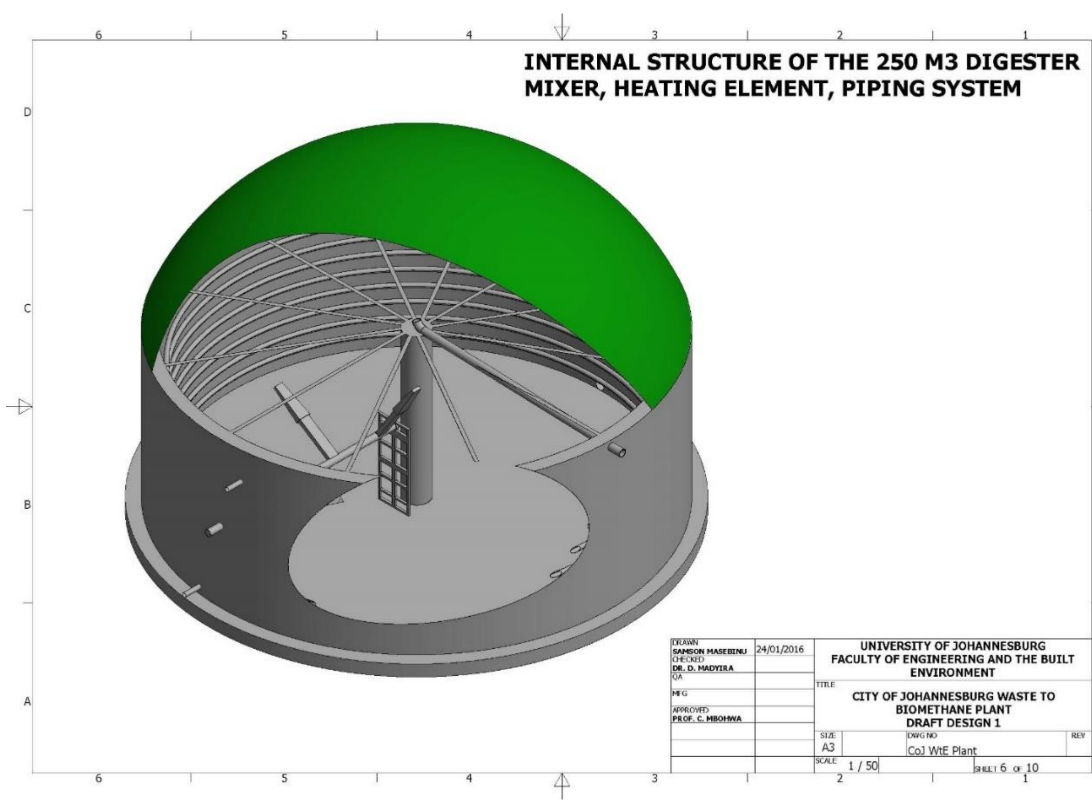


Figure 7-14 Cut out view with internal details of Digester

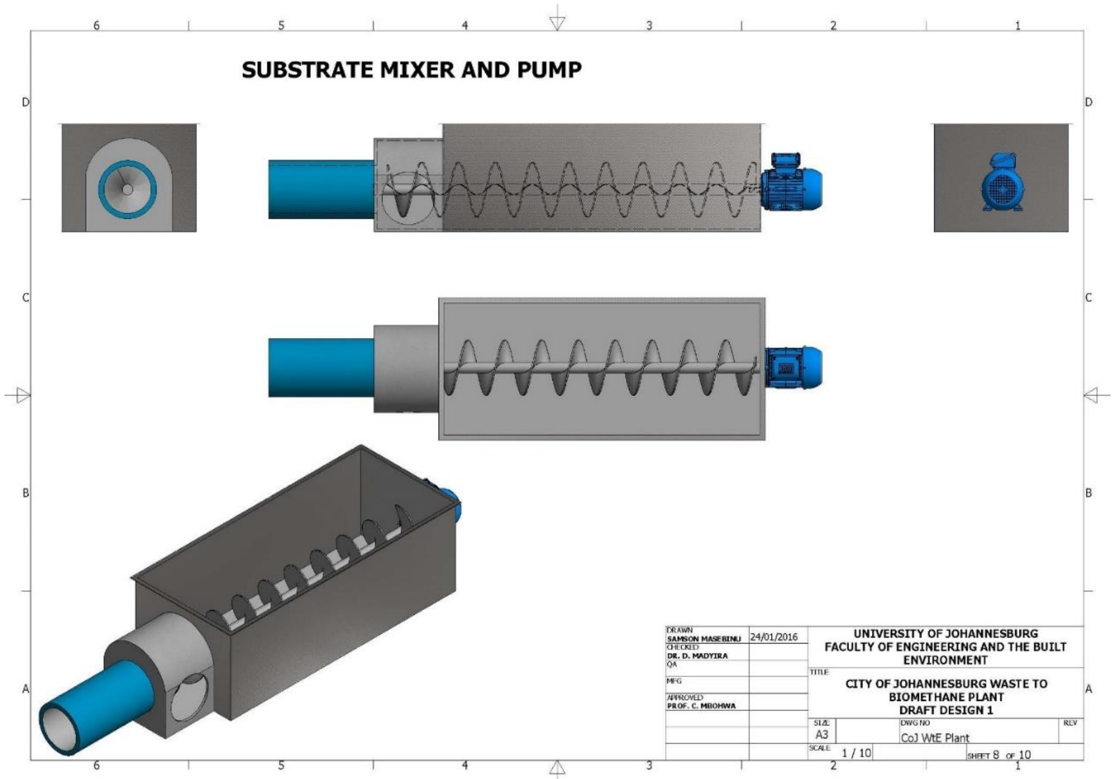


Figure 7-15 Representation of an auger feed pump

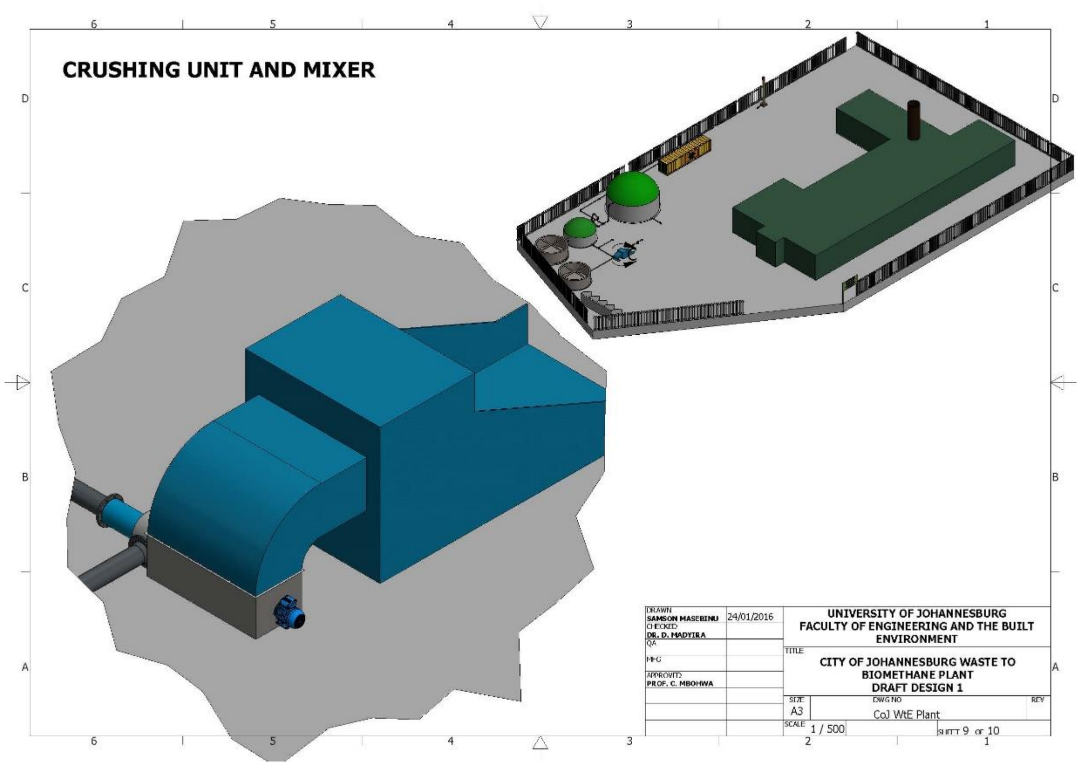


Figure 7-16 Representation of crushing unit connected to feed pump

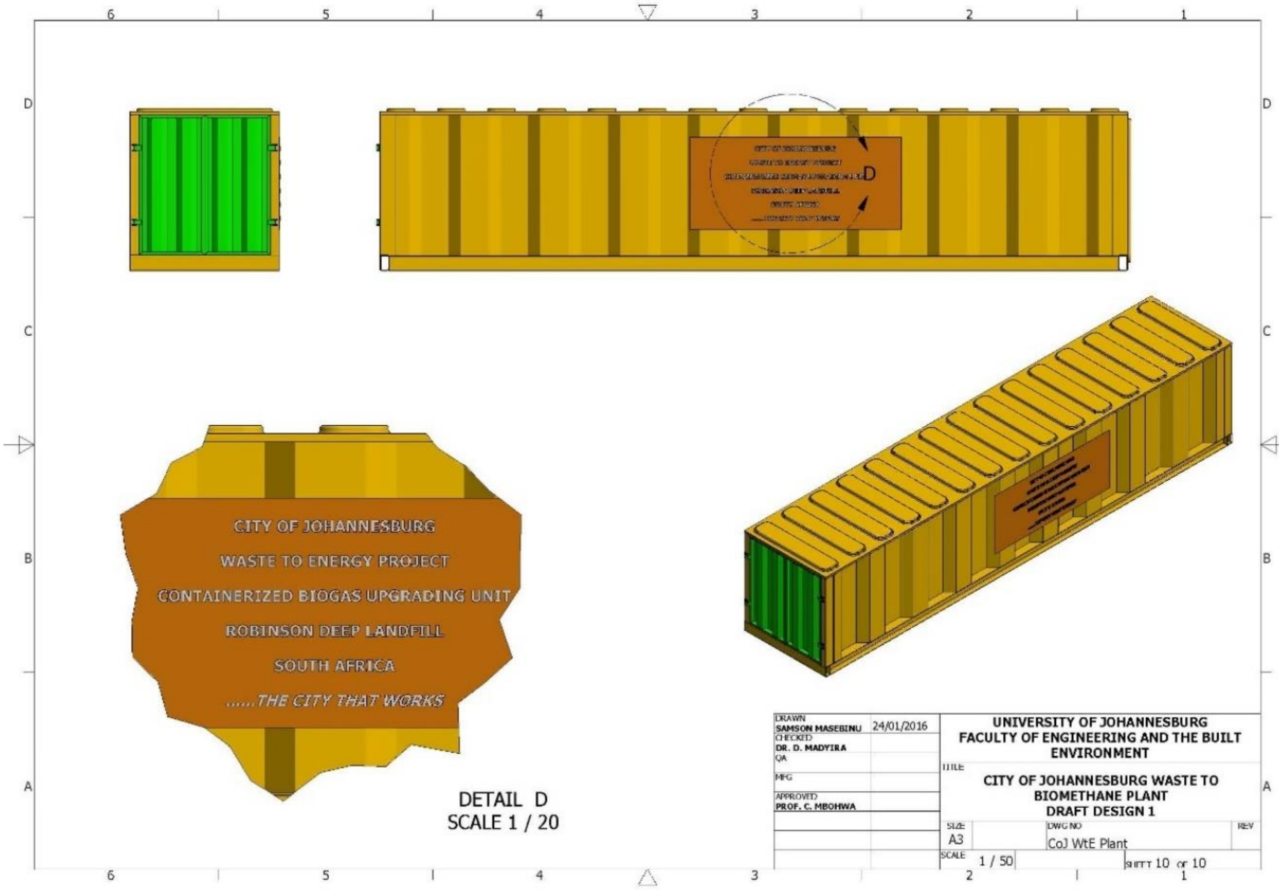


Figure 7-17 Containerised Biogas upgrading plant

8 Economic Analysis

Economic considerations of the plant depend on numerous factors. At this level of detail, only a coarse plant costing can be done. After rigorous search of literature, documented reports and historical cost of plants with similar capacity, the plant capital cost of $20,000/m^3 of biogas have been used as the base case estimate. The pilot plant biogas flow rate is 18.2 m^3/hr, hence the total capital cost is $364,650. The breakdown of the cost is presented in Table 8-1. Exchange rate of 1 USD = 17 ZAR has been used. As this cost is only based on 2% knowledge of the process equipment requirement and size a +/- 30% variation is plant capital cost is expected.

Table 8-1 Biogas upgrading plant capital cost

Cost Components	Percentage of cost	Cost in USD	Cost in ZAR
Civil works	10.00%	36,465.00	619,905.00
Waste collection and storage system	6.00%	21,879.00	371,943.00
Waste management equipment	3.00%	10,939.50	185,971.50
Mixing tanks	4.00%	14,586.00	247,962.00
Digester and it accessories	30.00%	109,395.00	1,859,715.00
Gas conditioning system and flaring system	3.70%	13,492.05	229,364.85
Heat exchanger and pumps	5.40%	19,691.10	334,748.70
Biogas upgrading system	17.80%	64,907.70	1,103,430.90
Biomethane compression and dispensing system	2.00%	7,293.00	123,981.00
Process control and instrumentation	3.90%	14,221.35	241,762.95
Control room building	2.20%	8,022.30	136,379.10
		320,892.00	**5,455,164.00**
Engineering	5.00%	18,232.50	309,952.50
Project permits and licences	2.00%	7,293.00	123,981.00
		346,417.50	**5,889,097.50**
Contingency	5.00%	18,232.50	309,952.50
		364,650.00	**6,199,050.00**

8.1 Engineering Scope of Plant

The bio-digesters and mixers will be made of concreate according to standard civil engineering structural design. The biogas upgrading plant with membrane module as the enrichment unit (i.e the separation of CO_2 and CH_4 only) with capacity for a capacity of 25m3/h will be a containerised modular plant. Due to the whole plant been a pilot plant and to reduce cost, the process pipelines will be manufactured from Class D and E PVC pipe. The low pressure pipeline will be made from 1" PVC Pipe and high pressure pipes will be 10 mm stainless steel pipe. The upgraded biogas will be stored in high pressure seamless steel cylinder with rated pressure in the excess of 250 bar. The plant will be equipped with programmable Logical control (PLC) unit, with full instrumentation integrated into a supervisory control and data acquisition unit (SCADA). Sampling points will also be incorporated into the design to enable ease of future research and inspection of process activities

9 Permitting

Once the technology has been selected, an engineering study must be performed to produce sufficient technical information (sizing, plant layout, drawings, and emission calculations) and to begin permitting procedures. UJ Biogas project developers will typically deal with the CoJ Municipality, the Ministry of Environment and possibly the Department of Energy. Municipalities issue building permits to ensure that building codes (structural, electrical, gas, etc.) are respected. Municipalities will deliver siting permits to ensure land use rules and building setbacks are respected. These permits may be conditional to obtaining certificate of authorization from the Ministry of Environment. Ministry of Environment required permit: Approval to bring waste onto the plant for processing, and Air Emissions Developers may also encounter zoning issues as depending on location.

South Africa has many elaborate plans and visions however despite this there remain significant policy gaps and areas where it appears there is a policy vacuum of sorts. There is a desperate need to synchronise these policies and plans into a more coherent strategy. Implementation and follow up becomes key and for this to happen a number of things must occur

9.1 Political Barriers

Since it is a carbon neutral renewable energy that can replace natural gas in vehicle applications, biomethane is unlikely to meet significant political barriers. The planned introduction of Carbon tax and commitment from the South African government to become carbon neutral further legitimizes the production of biomethane from waste in South Africa. Additionally, because biomethane can be used as vehicle fuel it should be recognized as a biofuel and shall also benefit from tax breaks, de-taxing and subsidies that the ethanol and biodiesel industries enjoy. Furthermore, because potential volumes will be relatively small, biomethane production is unlikely to upset gas producers or transporters.

9.2 Commercial barriers

With government and utilities embracing the production and commercialization of biomethane, the only significant barrier is its relatively higher price when compared to natural gas. However, with the introduction of carbon tax in the pipeline, biomethane will be able to compete with natural gas on price. This does not include any additional revenue from the potential sale of carbon credits. Accordingly, the development of a national green financial architecture would contribute considerably in accelerating South Africa towards a green economy by attracting private and international development finance through some domestic public investment (such as the commitment to South Africa's new National

Green Fund), thereby creating investor certainty, reducing barriers to scale and leveraging public procurement

10 Plant Site Selection

10.1 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;

10.1.1 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.

10.1.2 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 minimize 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.

10.1.3 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.

10.1.4 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.

10.1.5 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.

10.1.6 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.

10.1.7 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.

10.1.8 Accessibility

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

10.2 Proposed Site Location

The plant will be located at Robinson Deep. The preferred site has already been identified by CoJ project representative Mr. Thabo Mahlatsi. The aerial view of Robinson Deep Landfill is shown in Figure 10-1. A zoomed in image of the aerial view of the plant site is shown in Figure 10-2.

Figure 10-1 Aerial view of Robinson Deep landfill

Figure 10-2 Aerial view of proposed plant location

11 Environmental and Social Impact

Renewable energy is strategically viewed as an avenue through which the South African Government can respond to the challenge of climate change, improve energy security by diversifying sources of energy supply, and propel green growth through localization and empowerment. Bioenergy has potential to break the cycles of poverty by developing energy security, food security, job creation, income diversification and an integrated development.

The development of a biogas and biomethane industry within CoJ would stimulate economic development and funnel significant revenue into a local economy. In its quest to become carbon neutral, the city government could take a leadership role by producing biomethane at a premium in order to fuel its Bus fleet. Biomethane production from organic waste is a practical, sensible and inexpensive solution to mitigate GHG emissions and improve air quality in the City of Johannesburg.

Positive social impacts that would be evident as a result of venturing into bioenergy production includes the creation of employment in pre and post-plant implementation services to the CoJ by the appropriately trained students, local artisans, un-employed youth and entrepreneurs, through regular follow-up service, maintenance and repairs of plants. Generally, there is employment of skilled, semi-skilled and unskilled persons in the building and construction of the plant. Provision of clean and conservative energy is also another positive output. How local people are incorporated into future food/ fuel systems will be critical for determining whether modern bioenergy systems can deliver benefits to South Africa's poorest.

Outstanding social impacts where identified and government should strive to address as such: Working conditions should be improved by strengthen the regulations regarding the casual daily labourer, such as improvements on wage and benefits, health and safety standards, and rights for collective bargaining. Concerning the negative impacts on the well-being of local communities, it is absolutely necessary for the government to take the measures to fully recognize and protect the rights of local communities who might be threatened by the expansion of biofuels industry including land use change other environmental hazards and implications.

11.1 Impact of Plant

During the feasibility study, the most important social and environmental concerns, in order of priority, were: odours, truck traffic and air pollutants emission. The three highlighted points have been assessed towards how the neighbourhood will accept such project. The siting of the plant at Robinson deep will not reduce the traffic of truck around this environment but will assist in air pollution reduction. The dumping and mixing of waste in the mixing pit could create odour issues. To mitigate this potential problem, it would be recommended for the receiving pit to be as air tight as possible and equipped with a bio-filter to scrub any odours produced. Thus the construction and operation of an anaerobic digester should not present issues with the location of the plant.

Furthermore, if it could demonstrate responsible management practices, odour reductions and increased profitability for the CoJ, it is believed that this project would eventually be embraced all inhabitants of the CoJ.

11.2 Emission Reduction Potential

Assuming that all organic waste going to Robinson Deep landfill, 180,959 ton/yr, are diverted into an anaerobic digestion, CO_2 equivalent emission reduction will be 124,327.22 ton/yr. Other air pollutants could be avoided for using biomethane as vehicle fuel rather than landfilling and flaring, a practice currently been employed at Robinson Deep landfill is presented in Table 11-1. The estimation presented here is a conservative estimation of the GHG reductions from anaerobic digesters when compared to open-waste exposure and landfilling of organic waste.

Table 11-1 Air pollutant avoided for not flaring biogas produced by organic waste

	Flare emission factor (g/GJ)	Yearly emissions (kg/yr)
NO_x	19.7	5,783
SO_x	23.3	6,787
CO	2.4	699
PM10	36.9	10,748
PM2.5	36.9	10,748

12 Findings and Recommendations

The following are the findings from the study conducted:

- The waste quantification conducted indicated that all organic waste discharged at Robinson Deep Landfill are available for energy recovery as they are presently being covered with top soil to degenerate
- 34% of RCR waste were organic while only 14% of dailies, mostly from restaurants, were seen as organics
- JM waste contains about 93% organics which are also available for energy recovery
- Chemical properties of organic waste analysed indicated wet anaerobic digestion is most suitable
- If all organic wastes are converted into biomethane about 20% of the CoJ's 532 Metro buses can be fuelled, which is a conservative estimate.
- Sorting of organic fraction of RCR and Dailies will not cut jobs of exiting waste scavengers at Robinson deep as this class of waste is of no interest to them.

It is recommended that:

- High degree of sorting for RCR and Dailies is required to extract organic fraction of waste
- To reduce the task of sorting RCR and Dailies, awareness on source separation at household level is required
- Due to 93% of waste generated at JM been organic, which also require less sorting, anaerobic digestion of the whole waste should be considered in the near future
- To capture the actual tonnages of waste discharged at Robinson Deep Landfill, immediate commissioning of the weighing bridge should be prioritised.

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Appendix

A1 - Round Collected Refuse Waste Quantification Result Sheet

	WASTE TYPE	SAMPLE NUMBER (%)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL (%)
		ROUND COLLECTED REFUSE (RCR)															
	ORGANIC	Southdale	Norwood	Sandton 1	Doorfontein		Sandton 2	Hilbrow 1	Marlboro		Hillbrow 2	Alex1			Alex 2		
1	Food Waste	13.9	16.9	11.9	19.2	19.2	8.2	22.1	15.4	11.8	20.6	18.9	22.5	20.2	22.9	23.5	**17.81**
2	Garden Waste	5.3	8.4	11	3.1	13.8	11.9	0	4.2	26.4	0	0	23.8	17.5	2.3	13.9	**9.44**
3	Agricultural Waste	5.4	2.2	1.8	1.2	0	0	0	9.1	0	7.2	1.2	0	0	0	0	**1.87**
4	Remainder/Composite Organic Waste	8.9	3.4	2.1	1.1	0	3.3	10.7	0	0	5.1	18.6	0	0	19.9	0	**4.87**
		33.5	30.9	26.8	24.6	33	23.4	32.8	28.7	38.2	32.9	38.7	46.3	37.7	45.1	37.4	**34.00**
	PAPER & PAPERBOARD																
5	Newspaper	10.6	0	2.1	0	0	3.1	0	0	0	0	0	0	0	0	1.5	**1.15**
6	Cardboard/boxboard	0	0	0	0	0	1.9	0	0	0	6.5	0	0	0	0	0	**0.56**
7	Magazines/catalogues	2.2	0	5.6	0	0	4.2	0	0	0	0	0	2.7	0	0	0	**0.98**
8	Officepaper	1.6	0	13.7	0	0	14.4	1.2	0	0	1.1	0	3.8	0	0	0	**2.39**
9	Books	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0	0	**0.15**
10	Corrugated paper	12.4	9.9	0	5.9	0	8.2	0	4.9	15.9	8	0	0	0	0	10.9	**5.07**
11	Other/ miscellaneous paper	0	0	3.6	8.5	9.3	0	0	0	0	0	0	0	0	0	0	**1.43**
		26.8	9.9	25	16.7	9.3	31.8	1.2	4.9	15.9	15.6	0	6.5	0	0	12.4	**11.73**
	GLASS																
12	Clear containers/Bottles	2.8	2.9	9.8	4.9	0	3.6	0.9	5.2	7.4	7.2	8.8	5.3	10.9	9.8	11.9	**6.09**
13	Green containers/Bottles	0	9.9	8.7	0	2.9	0	6.9	3.9	0	0	2.3	0	0	0	0	**2.31**
14	Amber containers	0	0	0	0	0	0	0.5	0	0	0	2.8	0	0	0	0	**0.22**
15	Remainder/composite glass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		2.8	12.8	18.5	4.9	2.9	3.6	8.3	9.1	7.4	7.2	13.9	5.3	10.9	9.8	11.9	**8.62**
	METAL																
16	Tin/steel containers	0	1.9	0	2.8	1.9	1.1	0.9	0.2	0	3.2	8.8	1.3	0.8	0	0	**1.53**

17	Aluminum containers	6	3.8	0	3.1	0	2.2	6.1	8.3	0	2.7	8.8	2.2	6.9	0	3	**3.54**
18	Scrap metals	0	0	0	0	0	0	0.1	2.9	0	0	0	0	0	0	1.8	**0.32**
19	Other ferrous metal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
20	Other non-ferrous metal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		6	5.7	0	5.9	1.9	3.3	7.1	11.4	0	5.9	17.6	3.5	7.7	0	4.8	**5.39**
	PLASTICS																
21	Clear PET Bottles/containers	5.1	6.3	2.3	6.1	5.2	7.9	1.1	6.4	0	3.5	3.5	8.5	4.3	4.1	7.2	**4.77**
22	Green PET Bottles/containers	4.7	5.9	0	6	3.6	0	0	3.7	0	0	1.2	6.2	5.8	0	6.3	**2.89**
23	Amber PET Bottles/containers	0	0	0	3.9	3.2	0	0	0	0	0	0.5	0	0	0	0	**0.51**
24	HDPE containers	6.2	2.7	0	0	7.7	5.1	0	5.2	5.1	2.9	2.3	0	2.4	0	8.6	**3.21**
25	Film plastics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
26	Mixed plastic bags	5.3	5.9	10.5	5.3	4.9	6.4	1.4	4.3	0	3.7	6.3	3.4	1.4	3.1	0	**4.13**
27	Other plastics	2.4	0	4	3.7	0	6.8	1.6	0	19.6	1.8	0	6.9	1.4	2.3	0	**3.37**
		23.7	20.8	16.8	25	24.6	26.2	4.1	19.6	24.7	11.9	13.8	25	15.3	9.5	22.1	**18.87**
	TEXTILE/FABRIC/ LEATHER																
28	Textile	0	0	0	0	0	0	0.5	0	0	2.3	0	0	17.6	6.8	0	**1.81**
29	Shoes/Bags	0	0.9	0	0	5.9	0	0.6	0	0	1.6	0	0	0	0	0	**0.60**
30	Weavons	0	3	0	4.2	0	0	1.3	0	0	2.1	0	0	0	0	0	**0.71**
		0	3.9	0	4.2	5.9	0	2.4	0	0	6	0	0	17.6	6.8	0	**3.12**
	CONSTRUCTION & DEMOLITION MATERIAL																
31	Concrete	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
32	Lumber	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
33	Remainder/composite C & D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
	SPECIAL CARE WASTES																
34	Paint	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
35	Paint container	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**0.07**
36	Hazardous materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
37	Biomedical	0	0	0	0	0	0	1.1	0	0	1.3	0	0	0	0	0	**0.16**
38	Batteries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
39	Oil Filters	0	0	0	0	0	0	1.4	0	0	1	0	0	0	0	0	**0.16**

40	Remainder/composite S.C. waste	0	0	0	0	0	0	0	3.3	2.1	0	0	0	0	0	0	**0.36**
		0	0	0	0	0	0	2.5	4.3	2.1	2.3	0	0	0	0	0	**0.75**
	OTHER WASTES																
41	Waste Electrical Products (WEEE)	0	0	0	6.2	3.7	0	8.4	0	0	0	4.7	0	0	0	1.3	**1.62**
42	Tyre	0	0	0	0	0	0	20.9	0	0	12.2	0	0	0	0	0	**2.21**
43	Furniture/Bulky waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
44	Ceramics	2.2	0	0	0	1.2	0	0	0	0	0	0	4.8	0	0	0	**0.55**
45	Rubber	0	0	0	0	0	0	0	0	3.7	0	0	0	0	0	0	**0.25**
46	Carpet/rug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
47	Diapers/sanitary products	1.4	7.6	5.7	8.8	7.6	6.7	8.4	15.2	8	2.4	3.6	0	0	7.8	10.1	**6.22**
48	Wood/ply wood	0	0	0	0	4.8	0	2.3	0	0	3.6	0	3.2	0	7.5	0	**1.43**
49	Car seat/Automobile waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
50	Office chair	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
51	Polyurethane/ Extended polyurethane foam	3.6	0	0	0	0	0	0	0	0	0	0	0	0	6.7	0	**0.69**
52	Other/composite waste	0	8.4	7.2	3.9	5.1	5	2.1	6.8	0	0	7.7	5.4	10.8	6.8	0	**4.61**
		7.2	16	12.9	18.9	22.4	11.7	42.1	22	11.7	18.2	16	13.4	10.8	28.8	11.4	**17.57**
	TOTAL (%)	100	100	100	100.2	100	100	100.5	100	100	100	100	100	100	100	100	**100.05**

A2 - Dailies Waste Quantification Result Sheet

WASTE TYPE	SAMPLE NUMBER (%)										
	1	2	3	4	5	6	7	8	9	10	**TOTAL (%)**
ORGANIC											
Food Waste	12.8	12.6	7.8	10.3	6.3	10.6	9	10.4	13.3	8.3	**10.14**
Garden Waste	0	0	0	3	0	0	2.7	0	0	0	**0.57**
Agricultural Waste	5.2	6.3	5.8	0	0	3.5	5.6	5.9	0	5.1	**3.74**
Remainder/Composite Organic Waste	0	0	0	0	0	0	0	0	0	0	**0.00**
	18	18.9	13.6	13.3	6.3	14.1	17.3	16.3	13.3	13.4	**14.45**
PAPER & PAPERBOARD											

Newspaper	1.8	0	19.3	0	6	3.6	0	3.6	10	3.7	**4.80**
Cardboard/boxboard	0	0	5.1	1.1	0	0	9.5	0	13.3	6	**3.50**
Magazines/catalogues	0	0	0	0	0	0	0	0	0	8.2	**0.82**
Officepaper	2.2	2	0	5.7	0	8.4	0	0	6.1	0	**2.44**
Other/ miscellaneous paper	9.3	5.4	5.6	15.9	0	6	0	3.7	0	8.8	**5.47**
	13.3	7.4	30	22.7	6	18	9.5	7.3	29.4	26.7	**17.03**
GLASS											
Clear containers	14.4	8	7.4	0.9	0	3.5	0	7.1	7	6.3	**5.46**
Green containers	0	3	0	1.9	0	3.4	2.7	6.5	0	0	**1.75**
Amber containers	3	0	3.9	0	0	0	2.2	1.4	0	0	**1.05**
Remainder/composite glass	2	0	0	3	0	0	0	0	0	2.4	**0.74**
	19.4	11	11.3	5.8	0	6.9	4.9	15	7	8.7	**9.00**
METAL											
Tin/steel containers	8.8	2.8	3	0	10.8	0.5	6.6	7.1	0.8	0	**4.04**
Aluminum containers	0	0	5.1	5.3	0	4.6	0	6.3	7.2	3.1	**3.16**
Scrap metals	0	0	0	0	0	0	0	0	0	2.1	**0.21**
Other ferrous metal	0	0	0	0	0	0	0	0	0	0	**0.00**
Other non-ferrous metal	0	0	3.6	0	0	0	5.9	0	0	0	**0.95**
	8.8	2.8	11.7	5.3	10.8	5.1	12.5	13.4	8	5.2	**8.36**
PLASTICS											
Clear PET Bottles/containers	0	3.1	3.9	0.6	15.3	6.3	12.7	9.5	14	6.3	**7.17**
Green PET Bottles/containers	10	2	1.7	4	20.8	0	3.5	6.4	5.6	0	**5.40**
Amber PET Bottles/containers	0	0	0	2.7	0	0	5.6	0	0	0	**0.83**
HDPE containers	0	20	5.9	3	25.6	20	6	10	4	0	**9.45**
Film plastics	0	0	0	0	0	0	0	0	0	0	**0.00**
Mixed plastic bags	13.5	0	7.6	10.2	6.2	6.7	9.9	9	6.3	11.7	**8.11**
Other plastics	0	9.8	6	0	0	4.9	0	0	9.2	0	**2.99**
	23.5	34.9	25.1	20.5	67.9	37.9	37.7	34.9	39.1	18	**33.95**
TEXTILE/FABRIC/ LEATHER											
Textile	4.4	4.4	1.1	0	0	5.2	3.5	2.6	3.2	2.7	**2.71**
Shoes/Bags	0	0	0	0	0	0	4.5	0	0	0	**0.45**

Weavons	12.6	10.6	0	0	0	5.6	1.6	10.5	0	2.3	**4.32**
	17	15	1.1	0	0	10.8	9.6	13.1	3.2	5	**7.48**
OTHER WASTES											
Waste Electrical Products (WEEE)	0	0	0	3	9	0	0	0	0	0	**1.20**
Tyre	0	0	0	0	0	0	0	0	0	0	**0.00**
Furniture/Bulky waste	0	0	0	0	0	0	0	0	0	0	**0.00**
Ceramics	0	0	0	0	0	0	0	0	0	0	**0.00**
Rubber	0	0	0	0	0	0	0	0	0	0	**0.00**
Carpet/rug	0	0	0	0	0	0	0	0	0	0	**0.00**
Diapers/sanitary products	0	0	0	0	0	7.2	0	0	0	12.5	**1.97**
Wood/ply wood	0	0	0	0	0	0	0	0	0	0	**0.00**
Car seat	0	0	0	0	0	0	0	0	0	0	**0.00**
Office chair	0	0	0	0	0	0	0	0	0	0	**0.00**
Polyurethane/ Extended polyurethane foam	0	0	1.8	0	0	0	0	0	0	0	**0.18**
Roofing sheet	0	0	0	0	0	0	0	0	0	3.2	**0.32**
Automobile waste/safety kits	0	0	0	0	0	0	0	0	0	0	**0.00**
Other/Composite waste	0	10	5.4	29.4	0	0	8.5	0	0	7.3	**6.06**
	0	10	7.2	32.4	9	7.2	8.5	0	0	23	**9.73**
TOTAL (%)	100	100	100	100	100	100	100	100	100	100	**100.00**

A3 - Johannesburg Market Fruit and Vegetable Waste Quantification Result Sheet

WASTE TYPE	**SAMPLE NUMBER (%)**																															**TOTAL (%)**
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
ORGANIC WASTES																																
FRUITS AND VEGETABLES																																
Vegetables																																
GREEN																																

1	Artichokes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
2	Arugula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
3	Asparagus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
4	Broccoflower	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
5	Broccoli	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
6	Broccoli Rabe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
7	Brussels Sprouts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
8	Chinese Cabbage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
9	Green Beans	0	14.2	0	13.9	0	0	0	0	18	0	0	1	0	0	16.3	0	0	0	0	2.8	0	0	0	0	0	0	0	0	0	0	0	**2.14**
10	Green Cabbage	8.4	8.9	0	0	0	0	0.9	0	0	0	0	0.9	0	0	45.9	0	0	0	5.7	3.2	0	11.4	42.2	0	55.6	0	15.2	0	0	0	0	**6.40**
11	Celery	2.6	0	0	0	0	0	0	0	7.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16.4	0	0	0	0	**0.84**
12	Chayote Squash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
13	Cucumbers	3.9	0	7.7	0	0	0	2.8	0	0	0	0	0.7	20.2	0	0	0	0	0	0	0	6.5	0	0	0	0	32.5	0	20.2	0	0	0	**3.05**
14	Endive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
15	Leafy Greens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
16	Leeks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	0	0	0	0	0	0	0	16.4	0	10.4	0	5.2	**1.24**
17	Lettuce	6.9	9.1	0	0	0	0	0	0	5.3	8.57	0	3.4	0	0	0	0	0	0	0	0	8.1	0	0	0	0	0	0	0	0	9.5	0	**1.64**
18	Green Onions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
19	Okra	0	0	0	0	0	0	12.2	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15.2	0	**0.89**
20	Peas	0	0	0	0	0	0	0.9	0	0	1.68	0	0	0	0	7.6	0	0	0	0	0	10.2	8.8	0	0	0	0	0	0	18.2	0	0	**1.53**
21	Green Peppers	0	0	0	0	0	0	0	0	0	0	0	3.4	0	0	5.6	0	0	0	4.3	0	0	0	8.6	3.1	0	0	7.79	7.4	0	0	0	**1.30**
22	Snow Peas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
23	Spinach	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
24	Sugar Snap Peas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
25	Watercress	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
26	Zucchini	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		21.8	32.2	7.7	13.9	0	0	16.8	0	30.5	10.25	0	9.6	20.2	0	75.4	0	0	0	16.33	6	24.78	20.2	50.8	3.1	55.6	32.5	55.75	27.6	28.6	24.7	5.2	**19.02**
	Fruits																																

27	Avocados	1.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3.7	0	0	0	0	0	0	0	0	0	0	10.2	0	**0.64**
28	Green Apples	5.3	1.1	0	0	7.3	0	5.9	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	4.6	7.8	0	0	**1.13**
29	Green Grapes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
30	Honeydew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
31	Kiwifruit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
32	Green Peas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
33	Limes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		7.1	1.1	0	0	7.3	0	5.9	0	0	0	0	0	0	0	0	0	0	7	3.73	0	0	0	0	0	0	0	0	4.6	7.8	10.2	0	**1.77**
	FRUITS																																
	Blue/Purple																																
34	Blackberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
35	Blueberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
36	Black Currants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
37	Concord Grapes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
38	Dried Plums	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
39	Elderberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
40	Grape Juice	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
41	Purple Figs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
42	Purple Grapes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
43	Plums	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
44	Raisins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
	Vegetables																																
45	Black Olives	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
46	Purple Asparagus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
47	Purple Cabbage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
48	Purple Carrots	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
49	Eggplant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
50	Purple Belgian Endive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**

51	Purple Peppers	0	0	0	0	0	0	5	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.17**
52	Potatoes (purple fleshed)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
53	Black Salsify	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		0	0	0	0	0	0	5	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.17**
	Tan/Brown																																
	Vegetables																																
54	Shallots	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
55	Turnips	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
56	White Corn	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	9.7	0	0	5.1	0	0	0	0	0	0	0	0	0	0	0	0	**0.55**
57	Cauliflower	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
58	Garlic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
59	Ginger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
60	Jerusalem Artichokes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
61	Jicama	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
62	Kohlrabi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
63	Mushrooms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
64	Onions	0	0	0	10.2	2	0	8.7	0	0	24.4	2.8	0	0	0	0	0	0	0	0	6.4	0	0	0	0	0	0	0	0	0	7.8	0	**2.01**
65	Parsnips	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
66	Potatoes (White Fleshed)	0	18.2	9.3	31.7	2.3	0	0	0	0	0	0	22.9	0	19.3	0	0	37.7	2.7	41.0	0	0	8	0	0	0	0	0	10.3	0	0	12.7	**6.97**
		0	18.2	9.3	41.9	4.3	0	8.7	0	0	26.57	2.8	22.9	0	19.3	0	9.7	37.7	2.7	46.08	6.38	0	8	0	0	0	0	0	10.3	0	7.8	12.7	**9.53**
	Fruits																																
67	Bananas	14.3	0	0	0	14.7	0	3	0	0	0	0	0	0	0	0	81.9	0	1.5	0	0	0	0	0	0	0	0	0	19.3	17.5	0	19.4	**5.54**
68	Dates	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
69	White Nectarines	2.1	0	0	0	0	7.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.3	**0.48**
70	White Peaches	0	0	0	0	3.3	58	2.7	1.5	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	3.8	0	0	0	0	7.2	**3.34**
71	Brown Pears	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		16.4	0	0	0	18	65.4	5.7	1.5	0	0	0	0	0	0	0	81.9	0	28.5	0	0	0	0	0	0	0	3.8	0	19.3	17.5	0	31.9	**9.35**
	Yellow/Orange																																
	Vegetables																																

72	Yellow Beets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
73	Germ Squash	1.7	0	0	0	2.4	0	8.6	0	6.3	0	20.9	0	0	0	1.7	0	0	5.3	0	0	0	0	0	0	0	0	0	11.5	0	0	0	**1.88**
74	Carrots	15.2	14.5	19	2.5	3.2	0	0	12.2	0	0	6.2	12.8	29	46.3	0	0	0	0	0	0	46.9	0	0	40.8	36.4	0	0	0	3	8.8	0	**9.57**
75	Yellow Peppers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
76	Yellow Potatoes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
77	Pumpkin	0	0	0	0	0	0	14.1	0	19.9	38.6	0	4.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.4	**2.82**
78	Rutabagas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
79	Yellow Summer Squash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
80	Sweet Corn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
81	Sweet Potatoes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
82	Yellow Tomatoes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
83	Yellow Winter Squash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		16.9	14.5	19	2.5	5.6	0	22.7	12.2	26.2	38.56	27.1	17.4	29	46.3	1.7	0	0	5.3	0	0	46.85	0	0	40.8	36.4	0	0	11.5	3	8.8	10.4	**14.28**
	Fruits																																
84	Yellow Apples	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
85	Apricots	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
86	Cape Gooseberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
87	Cantaloupe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
88	Yellow Figs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
89	Grapefruit	0	0	0	0	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
90	Golden Kiwifruit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
91	Lemons	8.6	0.6	9.2	0	19.2	11.4	0	0	0	0.9	0	10.5	0	28.4	0	0	0	1.9	0	0	0	25.5	1.9	0	0	0	0	0	9.2	0	0	**4.11**
92	Mangoes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
93	Nectarines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.74**
94	Oranges	11.2	0	0	0	11.6	12.5	1.8	3.2	0	0	0.8	16.5	0	0	0	1.4	0	10.2	0	0	0	0	0	0	0	0	0	0	6.1	0	6.2	**2.63**
95	Papayas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
96	Peaches	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
97	Yellow Pears	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
98	Persimmons	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**

99	Pineapples	0	0	0	0	0	0	8.9	0	0	0	0	7.2	0	0	0	0	0	0.9	0	0	0	0	1.9	0	0	0	0	4.2	0	0	7.3	**0.98**
100	Tangerines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
101	Yellow Watermelon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
		19.8	0.6	9.2	0	30.8	23.9	10.7	3.2	0	0.9	0.8	34.2	0	28.4	0	1.4	0	36	0	0	0	25.5	3.8	0	0	0	0	4.2	15.3	0	13.5	**8.46**
	Red																																
	Vegetables																																
102	Beets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
103	Red Peppers	0	6.2	0	0	0	0	0	0	0	0	26.1	0	14.3	0	0	0	0	14.3	0	9.8	0	0	0	0	0	0	0	0	0	0	0	**2.28**
104	Radishes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
105	Radicchio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
106	Red Onions	0	0	9.2	0	0	0	0	71.6	0	0	12.2	0	0	0	12.2	0	0	0	0	32.3	0	0	0	0	0	0	0	0	0	0	15.4	**4.93**
107	Red Potatoes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
108	Rhubarb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
109	Tomatoes	0	13.3	20.3	0	3.8	0	0.3	0	0	0.7	17	11.2	0	0	0	0	56.3	0	0	0	0	0	0	0	0	0	0	0	10.2	23.3	0	**5.04**
		0	19.5	29.5	0	3.8	0	0.3	71.6	0	0.69	55.3	11.2	14.3	0	12.2	0	56.3	14.3	0	42.09	0	0	0	0	0	0	0	0	10.2	23.3	15.4	**12.26**
	Fruits																																
110	Red Apples	0	0	0	0	0	0	0	0	0	0	8.8	0	0	0	0	0	0	1.2	0	0	0	0	22	0	0	1.7	0	0	0	0	3.9	**1.21**
111	Blood Oranges	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
112	Cherries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
113	Cranberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
114	Red Grapes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
115	Pink/Red Grapefruit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
116	Red Pears	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**

117	Pomegranates	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
118	Raspberries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
119	Strawberries	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18.2	0	**0.59**
120	Parsley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**
121	Baby Sweet Melon	3.5	0	0	0	0	0	0	0	0	3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.22**
122	Spence Beck	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.9	0	1	0	0	0	0	0	0	**0.57**
123	Cape Fruits	2.5	0	0	0	0	0	0	0	0	8.5	0	0	0	0	0	0	0	0	8.7	0	0	0	0	0	0	0	0	0	0	0	0	**0.64**
124	Sweet Melon	1.2	0	0	7.6	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.31**
125	Paprika	0	5.7	12.7	0	9.7	0	10	0	18.7	0	0	0	0	0	0	0	0	0	0	12.8	0	0	0	0	0	16.9	0	0	0	0	0	**2.79**
126	Watermelon	0	0	5.6	8.7	8.8	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	5	3.4	23.1	0	0	24.1	0	0	0	0	**2.55**
127	Peeled Beans	0	0	0	15.4	0	0	0	6.5	0	0	0	0	0	0	5.7	0	0	0	0	0	0	18	0	0	0	0	14.0	0	0	0	0	**1.92**
128	Citrus	0	0	0	0	4.7	3.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.3	0	0	0	0	0	0	0	12.6	0	0	**0.75**
129	Beetroot	0	0	0	0	0	0	4.5	0	0	0	0	0	30.5	0	0	0	0	0	0.0	0	0	3	0	27	0	0	0	5.2	0	0	0	**2.26**
130	Bell Pepper	0	0	0	0	0	0	4.7	0	0	0	0	0	0	0	0	0	0	0	3.2	0	5.6	0	0	0	0	0	0	0	0	0	0	**0.44**
131	Baby Marrow	0	0	0	0	0	0	0	0	10	3	0	0	0	0	0	0	0	0	4.5	8.3	0	3.7	0	0	0	12.7	0	2.1	0	0	0	**1.43**
132	Crisp Lettuce	0	0	0	0	0	0	0	0	9.6	0	0	0	0	0	0	0	0	0	5.8	10.4	5.7	4.3	0	0	0	0	0	3.9	0	0	0	**1.28**
133	Baby Hub-Suqce	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.7	7	8.7	6.3	0	0	0	25.4	0	3.3	0	0	0	**1.82**
		11	5.7	18.3	31.7	23.2	3.7	19.2	6.5	38.3	15.6	8.8	0.5	30.5	0	5.7	0	0	1.2	27.9	38.5	22.3	40.3	38.3	50.1	1	56.7	38.1	14.5	12.6	18.2	3.9	**18.78**
	Other Waste																																
134	Process food	1	0	0	0.7	0	0	0.8	0	0	0	0	0	0	1.2	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.14**
135	Paper & Paper board	3.8	4.2	3.5	2.2	3.7	4.3	0	2.9	2.2	3.8	3.7	2.8	3.2	0	0	3.8	4.8	3.2	3.6	4.2	3.45	2.4	2.9	2.4	4.4	4.2	3.1	4.2	3.7	2.9	1.8	**3.08**
136	Plastic & Plastic crates	2.4	2.1	0	2.6	0	1.4	2.9	0	1.3	0	0	1.8	0	3.1	2.8	0	1.8	1.8	2.4	0	0.9	1.6	0	1.5	0	0.7	1.4	0	1.1	0	3.2	**1.19**
137	Wood	0	0	3.6	3.4	0	0	0	2.2	0	4.2	0	0	2.8	0	0	3.6	0	0	0	3.4	0	0	4.6	2.2	3.1	0	0	4.2	0	3	0	**1.30**

138	Metal	0	1.9	0	0	1.6	1.3	1.3	0	0	0	0	0	0	1.6	2.1	0	0	0	0	0	1.8	0	0	0	0	0	0	0	0	0	1.7	**0.43**
139	Other composite	0	0	0	1.3	2.2	0	0	0	2.3	0	2.1	0	0	0	0	0	0	0	0	0	0	2.1	0	0	0	2.3	1.8	0	1.1	1.6	1.1	**0.58**
		7.2	8.2	7.1	10.2	7.5	7	5	5.1	5.8	8	5.8	4.6	6	5.9	5.65	7.4	6.6	5	6	7.6	6.15	6.1	7.5	6.1	7.5	7.2	6.3	8.4	5.9	7.5	7.8	**6.71**
	TOTAL	**100.2**	**100**	**100.1**	**100.2**	**100.5**	**100**	**100**	**100.1**	**100.8**	**100.57**	**100.6**	**100.6**	**100**	**99.9**	**100.65**	**100.4**	**100.6**	**100**	**100.04**	**100.57**	**100.08**	**100.1**	**100.4**	**100.1**	**100.5**	**100.2**	**100.15**	**100.4**	**100.9**	**100.5**	**100.8**	**100.32**

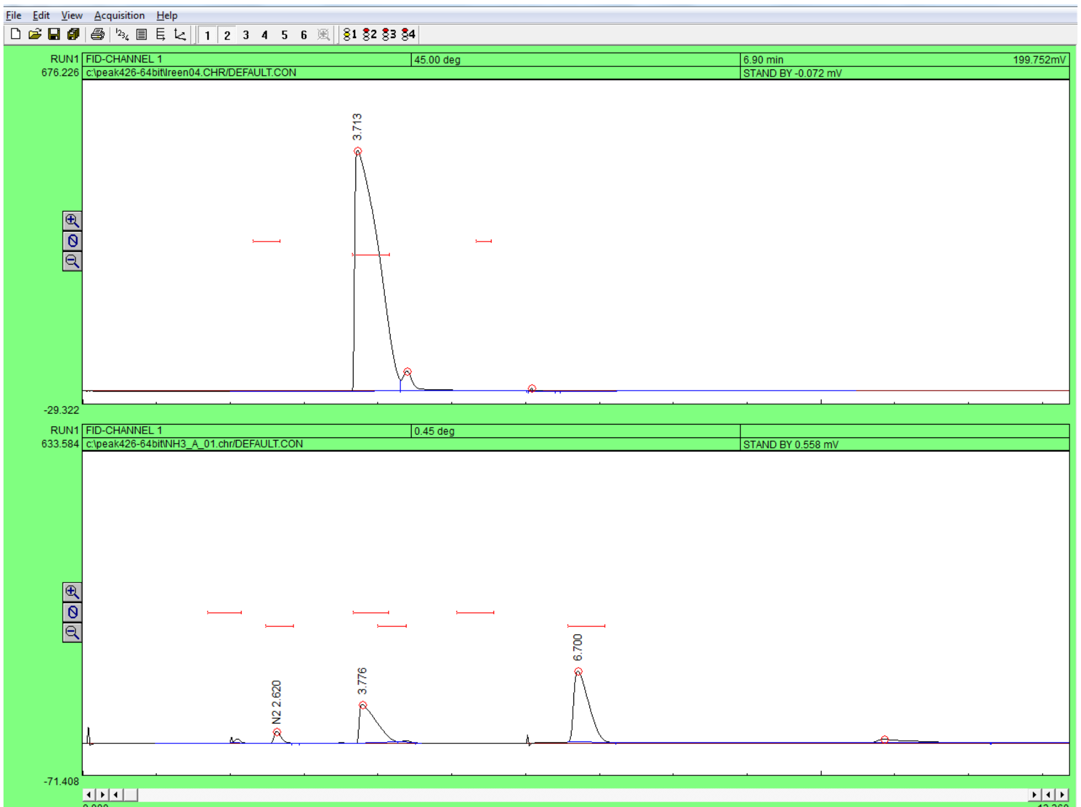
A4 - Proximate and Ultimate Analysis for Robinson deep Landfill

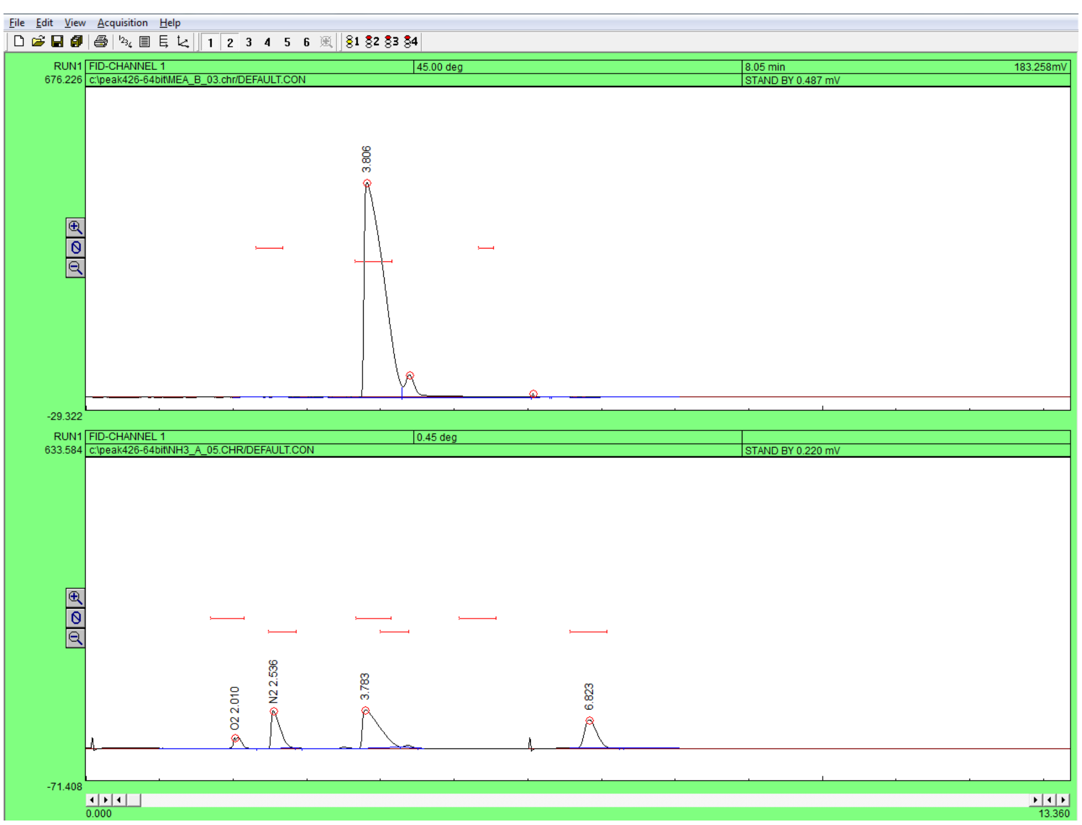
	Proximate Analysis for Robinson Deep RCR, Dailies and Garden Waste							Ultimate Analysis for Robinson Deep			
Source	Wet (g)	Dry (g)	Ash (g)	MC (%)	TS (%)	VS (% of TS)	VS (% of Wet)	C	H	N	C/N
Garden	100	29.26	6.93	70.74%	29.26%	76.32%	22.33%	19.67	5.36	1.96	10.04
Mixed Waste	100	27.33	5.75	72.67%	27.33%	78.96%	21.58%	13.25	6.25	0.91	14.56

A5 - Proximate and Ultimate Analysis for JM

Proximate analysis for JM fruit and Vegetable waste								Ultimate Analysis for JM Fruit and veg			
Source	Wet (g)	Dry (g)	Ash (g)	MC (%)	TS (%)	VS (% of TS)	VS (% of wet)	C	H	N	C/N
Leek	100	8.47	1.34	92%	8%	84%	7%	43.51	5.43	3.28	13.27
Carrot	100	10.27	2.59	90%	10%	75%	8%	42.75	5.8	2.3	18.59
Chilly	100	13.63	2.35	86%	14%	83%	11%	42.69	5.74	1.79	23.85
Lettuce	100	4.32	0.5	96%	4%	88%	4%	47.12	6.69	1.52	31.00
Potatoes	100	22.67	0.99	77%	23%	96%	22%	44.5	5.44	2.4	18.54
Squash	100	7.31	1.21	93%	7%	83%	6%	45.88	6.25	4.25	10.80
Pepper	100	9.91	1.35	90%	10%	86%	9%	42.63	5.77	1.57	27.15
Lemon	100	20.23	2.47	80%	20%	88%	18%	47.1	6.09	1.79	26.31
Baby melon	100	7.42	1.58	93%	7%	79%	6%	44.06	5.86	1.96	22.48
Cabbage	100	15.5	3.01	85%	16%	81%	12%	48.73	7.07	3.3	14.77
Tomatoes	100	4.46	1.34	96%	4%	70%	3%	48.01	6.52	2.21	21.72
Satsuma (Naartjie)	100	17.77	9.77	82%	18%	45%	8%	43.32	5.5	3.19	13.58
Beetroot	100	9.49	2.53	91%	9%	73%	7%	46.33	5.98	1.83	25.32
Pea	100	18.54	4.29	81%	19%	77%	14%	44.04	5.9	0.95	46.36
Sweet melon	100	11.39	1.99	89%	11%	83%	9%	41.9	7.03	2.61	16.05
Bananas	100	17.46	6.31	83%	17%	64%	11%	40.19	5.73	3.57	11.26
Cucumber	100	3.63	2.19	96%	4%	40%	1%	44.93	5.84	1.5	29.95
Watermelon	100	2.97	1.06	97%	3%	64%	2%	47.08	6.08	1.73	27.21
Beans	100	37.61	2.72	62%	38%	93%	35%	40.61	3.25	1.11	36.59

A6 - Gas Chromatography Result Screenshot for BMP Analysis





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