Bio-Methane Potential of Exotic Food Waste and Water Hyacinth

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Abstract

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Region specific foods in the Niger Delta like yam and cassava are consumed on a daily basis by at least 70% of the population. In addition to other commonly consumed foods, high volumes of unavoidable food wastes are generated. With 78% of the households in the region disposing their waste by burying, burning or in unauthorised heaps, environmental degradation is sustained. The region also suffers an infestation of Water Hyacinth (WH). Anaerobic Digestion (AD) presents a viable way of managing these wastes in addition to providing a clean source of energy. Limited research has been conducted on the characterisation and biogas potential of these exotic food wastes due to their localised availability, leading to a knowledge gap. My original contribution to knowledge is the Specific Waste Index (SWI), nutrient characterisation and biogas potential of the local food wastes and WH. Also novel is the design and optimisation of the AD process for mono and co-digestion including the quarter hourly analysis of CH_4 and CO_2 content of the biogas composition over the complete duration of an AD test.

The research approach was experimental and involved using conventional research methods in new fields of investigation. SWI was determined by replicating local food processing practices while nutrient composition was obtained using standard analytical methods. The Bio-Methane Potential (BMP) tests were carried out on the four most common food wastes, Yam Peel (YP), Cassava Peel (CP), Cocoyam Peel (CoP), Plantain Peel (PP), following VDI 4630 guidelines and using a newly designed cost-effective bioreactor. Laboratory scale batch reactors ran over 20 days at 37^{O}C (310 K). The food wastes were anaerobically co-digested with WH in the ratio 2:1 g Volatile Solid (VS) with a total substrate mass of 8.4 g VS. The S:I ratio was 1:2 g VS and tests were carried out in duplicates to give an indication of repeatability.

The results showed a wide range of SWI from 0.2-1.5. The Total Solid (TS) content varied from 7% for WH to 82% for Egusi Shell. Crude Protein and Crude Fibre were highest for Ugwu Stalk at 37% VS and Egusi Shell at 82% VS respectively. Cassava Peel had the highest oil content at 25% VS. NFE which was the major nutrient for 80% of the samples was highest for Yam Peel at 82% VS. YP+WH, CP+WH, CoP+WH and PP+WH had specific biogas yields of 0.42, 0.29, 0.39, and 0.38 m^3/kg VS respectively. The yields represented 76%, 48%, 70% and 69% of their respective theoretical values. The samples had their highest methane content during the Technical Digestion Time (T80) period, which lasted up to the 8^{th} day of digestion. The pH values ranged from 7.3 to 7.9 indicating that there was no inhibitory accumulation of organic acids. The results of the mono-digestion tests showed that co-digestion with WH reduced the biogas yields for YP, CP, CoP and PP by 16%, 22%, 7% and 7%. This drop in gas production was due to presence of complex molecules in the WH co-substrate, which cannot be digested by the anaerobic microbes. Further tests showed that fresh waste produced more biogas than dry samples, while a lower S:I produced more biogas due to increased microbial population.

It was concluded that waste and nutrient content varied widely between different types of Niger Delta foods. In addition mesophilic digestion of food wastes have good biogas potentials which reduce when co-digested with water hyacinth. The methane content is shown to vary widely throughout an AD test. The findings of this research would provide valuable information to AD databases and its implementation would support clean energy production, environmental remediation and allow researchers in poor regions to perform BMP test on novel feedstock using cost-effective reactors.

Key Words: Anaerobic Digestion, Co-Digestion, Water Hyacinth, Niger Delta, Yam, Cassava, Cocoyam, Food Waste, Specific Waste Index, Biogas.

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List of Publications

Conference Presentations

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Dedication

This thesis is dedicated to my daughter Pallat, wife Tangyen, and the whole Longjan family.

Declaration

I hereby declare that the research presented in this thesis is the original work of the author and that the work described herein has not been previously submitted as part of the requirement for an award or higher degree in this or any other university. The research work was conducted solely by the undersigned except where otherwise specified, or where acknowledgments are made by references.

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Date: 8/8/16

Nomenclature (with units)

CF	Crude Fibre	(%)
CFd	Crude Fibre Digestibility Factor	(%)
CP	Crude Protein	(%)
CPd	Crude Protein Digestibility Factor	(%)
DC	Digestible Carbohydrates per Dry Matter Basis	(kg/10^3 kg)
DCv	Digestible Carbohydrates per Volatile Solid	(kg/kg VS)
df	Degrees of freedom	
DO	Digestible Crude Fat per Dry Matter Basis	(kg/10^3 kg)
DOv	Digestible Crude Fat per Volatile Solid	(kg/kg VS)
DP	Digestible Crude Protein per Dry Matter Basis	(kg/10^3 kg)
DPv	Digestible Crude Protein per Volatile Solid	(kg/kg VS)
GCVM	Gross Calorific Value of Methane	(MJ/kg)
GYC	Gas Yield of Carbohydrates	(10^{-3} m^3/kg VS)
GYCf	Gas Yield Conversion for Carbohydrates	(10^{-3} m^3/kg OS)
GYO	Gas Yield of Fat	(10^{-3} m^3/kg VS)
GYOf	Gas Yield Conversion for Fats	(10^{-3} m^3/kg OS)
GYP	Gas Yield of Proteins	(10^{-3} m^3/kg VS)
GYPf	Gas Yield Conversion for Proteins	(10^{-3} m^3/kg OS)
MC	Methane Share for Carbohydrates	(%)
MCf	Methane Content of Biogas for Carbohydrates	(%)
MO	Methane Share for Oils	(%)
MOf	Methane Content of Biogas for Fats	(%)
MP	Methane Share for Proteins	(%)
MPf	Methane Content of Biogas for Proteins	(%)
NFE	Nitrogen Free Extracts	(%)
NFEd	Nitrogen Free Extracts Digestibility Factor	(%)
OAH	Crude Fat	(%)
OAHd	Crude Fat Digestibility Factor	(%)
P-value	Calculated Probability	
ppmv	parts per million by volume	
R^2	Coefficient of Determination	
R^2_{adj}	Adjusted Coefficient of determination	
RMSE	Root Mean Square of Errors	
S:I	Substrate to Inoculum ratio	
SS	Sum of squares due to the source	
t	Time	(days)
T80	Technical Digestion Time	(days)
TGY	Total Gas Yield	(10^{-3} m^3/kg VS)
TMC	Total Methane Content	(%)
VS	Volatile Solids	(%)

Abbreviations

AD	Anaerobic Digestion
AOAC	Association of Official Agricultural Chemists
ASTM	American Society for Testing Materials
BMP	Bio-Methane Potential
BS	Bean Skin
CCH	Corn Cob and Husk
CHP	Combined Heat and Power
CP	Cassava Peel
CP+WH	Cassava Peel and Water Hyacinth
CoP	Cocoyam Peel
CoP+WH	Cocoyam Peel and Water Hyacinth
CSTR	Continuously Stirred Tank Reactor
DMB	Dry Matter Basis
DMRT	Duncan's Multiple Range Test
ES	Egusi Shell
FW	Fresh Weight
GH	Groundnut Husk
LCFA	Long Chain Fatty Acid
LSD	Least Significant Difference
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate
NBS	National Bureau of Statistics
ND	Niger Delta
NDIR	Non-Dispersive Infrared
NERC	National Electricity Reform Commission
NNPC	Nigerian National Petroleum Cooperation
NPC	National Population Commission
PP	Plantain Peel
PP+WH	Plantain Peel and Water Hyacinth
RE	Renewable Energy
SCFA	Short-Chain Fatty Acid
SWI	Specific Waste Index
TMS	Total Mass of Slurry
TS	Total Solids
US	Ugwu Stalk
VFA	Volatile Fatty Acids
WH	Water Hyacinth
YP	Yam Peel
YP+WH	Yam Peel and Water Hyacinth

Chapter 1 Introduction

The chapter introduces the research thesis. The background to the research is presented, while the aims and objectives of the study are outlined. Motivations for undertaking the study are also identified. The structure of the thesis is presented, while its novel contribution to the scientific community is highlighted.

1.1 Background

In the last two hundred years, overconsumption of natural resources is depleting the world's reserves of raw materials. This has led to an unprecedented increase in the various types and volumes of pollution (Markham, 1994). Post Industrial Revolution years have seen a high increase in burning of fossil fuels and land use change. These have led to a significant increase in atmospheric carbon dioxide from pre-industrial values of 279 ppmv to 369 ppmw (Cowie, 2012). These processes threaten future generations and their ability to meet their energy needs. This has led nations to unite and promote responsible methods of resource utilisation. Specifically targeted is the use of renewable energy sources.

Nigeria is one country that has experienced environmental degradation from natural resource extraction. The nation is one of the largest producers of crude oil. Despite the abundant oil reserve, the country's energy sector struggles to meet energy demands. 52% of the population have no access to electricity while 75% of the population utilise traditional biomass for cooking (IEA, 2013). This biomass consists of firewood and charcoal. The use of such traditional fuels is the major factor leading to an increase in desertification and change in the country's vegetation (GOPA, 2015).

Between the years of 1980 and 2012, Nigeria has generated a total of 168 billion kilowatt hours (EIA, 2016). Table 1-1 shows the current power generating capacity of 23 grid-connected stations in the Nigerian Electricity Supply Industry (KPMG, 2013).

Table 1–1 Generating capacity of power plants in Nigeria.
Note: Data from KPMG, 2013.

Power Sources	Installed Capacity (MW)	Available Capacity (MW)
Thermal	8,457.6	4,996.0
Hydropower	1,938.4	1,060.0
Total	**10,396.0**	**6,056.0**

The total installed power capacity is 10,396 MW. Thermal Power accounts for 81% of the total installed capacity while Hydropower accounts for 19%. In both systems, the full potential of the generating plants are not being achieved. This contributes to the power deficit of the country. Harnessing

renewable energy in Nigeria would help in addressing the energy shortfall. The clean energy would also mitigate environmental degradation from burning of traditional fuels.

With the current research and optimisation of various renewable energy technologies, their usage is wide spread. This has led to a reduction in implementation costs. In view of that, the renewable energy potentials of Nigeria have been estimated in the Renewable Energy master Plan (REMP, 2012) and are presented in Table 1-2.

Table 1–2 Renewable energy potentials of Nigeria.
Note: Data from REMP, 2012.

Renewable Energy Technology	Energy Potential
Large Hydropower	11,250 MW
Small Hydropower	3,500 MW
Solar	4.0 – 6.4 kWh/m^2/day
Wind	2.4 m/s at a height of 10 meters on the mainland
Municipal Waste	0.5 kg/capita/day
Animal Waste	245 million assorted animals as of 2001
Agricultural residues	91.4 million tonnes/ year produced
Energy crops	28.2 million hectares of arable land; 8.5% cultivated

Currently the exploitation and utilisation of these renewable technologies in the country is low and limited to pilot and demonstration projects. Sambo (2008) suggests that the major hindrance to the large-scale exploitation of renewable energy is the absence of appropriate policy, regulatory and institutional frameworks. Furthermore Oseni (2012) concludes that to improve large-scale utilisation of renewable energy in Nigeria, there is need for technical assistance from industrialised developing countries. Multilateral institutions would also need to advance renewable energy technologies in the Nigeria. Oseni advised that government at all levels must be committed to the utilisation of renewable energy sources. Additionally its progress and performance has to be continuously reviewed for proper policy formulation. Mohammed et al. (2013) recommended that feed-in-tariffs, tax credits and renewable portfolios could increase the share of renewable energy in Nigeria's power generation mix. The aim of the strategy would be to lower the cost of renewable energy while increasing the adoption of renewable technologies.

In Nigeria, the adoption of renewable technologies is much needed in the Niger Delta region. The area is home to Nigeria's crude oil deposits and has suffered from environmental degradation. This region is located on the southern coast of Nigeria and has experienced adverse effects from oil spills and gas flaring. In addition to pollution from the oil and gas sector, the Niger Delta, which is located on a delta, has suffered from the infestation of water hyacinth. The invasive species has infiltrated the numerous water bodies in the region. Its presence has led to negative effects on the socio-economic

activities of the region. Another adverse effect of the watery terrain of the region is the difficulty it causes in extending the national power grid to the remote Niger Delta communities. The consequence is a lack of adequate power in the region, which further promotes the use of fire wood, enhancing deforestation. The absence of electricity forces local households to utilise fuel based electric generators that further pollute the atmosphere with noxious greenhouse gases. Notably another source of pollution in the region results from the indiscriminate disposal of domestic and communal wastes. The lack of official policies on waste disposal has led to unsanctioned disposal methods including dumping waste into the water bodies and burning of household waste.

These energy utilising and environmental degrading activities in the Niger Delta have the potential to deprive future generations of energy sources and healthy living conditions. Studies have shown that improved energy improves security, health and education and reduces poverty. There is a positive link between rural electrification, rural development, poverty alleviation and reduced environmental degradation (Cecelski and Unit, 2000; IEG, 2008). Furthermore transition to low-carbon systems in rural locations, potentially leads to greater human development (Casillas and Kammen, 2010). Selecting the ideal renewable energy solution for the region involves considering factors such as technical complexity, environmental impact and operational risk.

Biofuels produced from the anaerobic digestion of organic waste addresses most of the environmental degradation issues mentioned above. Bioenergy is obtained from biomass, which has been described as the “ore of energy” (Anderson and Tillman, 1977). The biomass in this case would consist of the communal wastes and the abundant water hyacinth. Utilising water hyacinth as a feedstock would aid in mitigating its infestation in the region. Furthermore the soil, water and atmosphere will benefit from the reduction in burying, dumping and burning of waste respectively. The utilisation of these feedstocks would produce clean biogas that would help meet the energy demand of remote communities. An additional benefit of the process is the production of nutrient rich digestate which farmers may utilise as soil conditioners for their farms. Alternatively the digestate may be sold to raise funds for the running costs of the bioenergy system. For regions that have poor energy infrastructure, biogas from AD can reduce the dependence on fossil fuels and help mitigate deforestation while improving the livelihood of rural populations (Thien Thu et al., 2012). Biogas from waste has been shown to reduce poverty and improve on the economic development in developing countries (Teune, 2007).

There has been extensive research in the field of anaerobic digestion and biogas potentials of substrates. These studies have utilised feedstock which

are common in the developed countries. They include energy crops, industrial waste and sewage sludge. There has been limited research on the biogas potentials of exotic food wastes found in rural Nigerian communities. This may be a result of laboratories in developing countries having almost no access to advanced gas measuring equipment which limits research aimed at improving local biogas production (Pham et al., 2012). Local foods such as *acha*, millet, guinea corn, *ugwu*, *egusi*, which are commonly consumed in Nigeria, produce organic wastes. Furthermore the FAOSTAT (2015) database indicates that Nigeria is the world's largest producer of yam, cassava, cocoyam, egusi, beans and third largest of groundnut. Additionally the country produces some of the highest volumes of plantain and corn. The foods will undoubtedly produce high amounts of waste. These potential biofuels can be used as feedstock for the anaerobic digestion process. The numerous varieties of possible feedstock for biogas production demonstrate the need for detailed characterisation of each potential feedstock (Drosg et al., 2013). The distribution of protein, fats and carbohydrates in feedstock is important for assessing its fitness for the AD process (Steffen et al., 1998). Furthermore feedstock composition can be used to determine the retention time of a digester based on the various digestibility rates of different nutrients. Simple sugars, volatile fatty acids and alcohols are digested in hours, proteins and lipids in days while cellulose takes weeks to anaerobically degrade (Al Seadi et al., 2013). If data on the feedstock is available, it can be used for an initial evaluation of the suitability of the feedstock. This creates a need for the characterisation of Niger Delta food wastes and water hyacinth for the benefit of researchers and potential AD investors. Furthermore the literature on the co-digestion of water hyacinth focuses on its synergistic effects on animal manure. There is limited data on the effects of co-digesting the plant with food waste. This thesis aims to contribute data to fill that research gap.

The limited studies on the anaerobic digestion of Nigerian food wastes comprises of studies that do not follow standard methods of testing, consisting of results with no evidence of repeatability. The results from such research in developing countries may not reach international standards preventing them from being published in international peer reviewed journals (Pham et al., 2012). The results of this thesis will contribute data to fill that research gap by identifying the common food wastes in the Niger Delta and evaluating their biogas potentials. The focus will be on the characterisation and anaerobic co-digestion of water hyacinth and region specific food wastes common to the Niger Delta. The research approach is experimental and shall involve using conventional research methods in a new area of investigation.

1.2 Motivation for research

The motivation for this study is to fill the research gap created by the lack of quality data on the characteristics and bioenergy potential of food wastes common to the Niger Delta. Further motivations for selecting the region and the renewable technology are listed:

1.2.1 Motivation for selecting the Niger Delta region:

1. The Niger Delta has suffered extensive environmental degradation from the extraction of crude oil and gas flaring.
2. The watery terrain of the region limits the extension of the national grid, leading to insufficient power, which promotes further use of traditional biomass.
3. The invasive water hyacinth has thrived in the conducive environment of the Niger Delta.
4. The region suffers from the effects of improper waste disposal methods. These wastes will serve as feedstock for the AD process.

1.2.2 Motivation for selecting AD as a Renewable Technology:

1. Anaerobic digestion will provide a clean source of energy while mitigating the adverse effects of water hyacinth infestation and improper waste disposal.
2. AD technology is cost effective and easier to commission in poor rural communities.
3. AD systems require limited specialised expertise for their daily operations. They can be managed in remote locations where the literacy rates are low.
4. The warm climate of the Niger Delta would support low heating demands for mesophilic AD systems thereby conserving energy.
5. The digestate from the digester may be utilised by local farmers as a soil conditioner on their farmlands.

1.3 Research Aim, Objectives and Scope

1.3.1 Aim of Research

The aim of this research is to determine the biogas potential of common Niger Delta food wastes.

1.3.2 Objectives of Research

1. To identify commonly consumed foods in the Niger Delta and determine their Specific Waste Index using local food preparation processes.
2. To characterise the food wastes and evaluate their theoretical bio-methane potentials.
3. To quantify the food waste on a regional level and calculate their regional renewable energy potential.

4. To design and build effective low-cost laboratory scale bioreactors for the AD tests which can be rebuilt by Nigerian researchers.
5. To determine the biogas potentials of co-digested food wastes and water hyacinth.
6. To determine the biogas yields of mono-digested food wastes and analyse the effect of water hyacinth on their biogas production.
7. To determine how the moisture content and substrate to inoculum ratio affects biogas production.
8. To analyse the existing policies and regulations that would support the development of renewable energy generation in the Niger Delta.

1.3.3 Scope of Thesis

The research scope focuses on exploring the bio-methane potential of the common food wastes in the Niger Delta. This is accomplished by identifying the common foods in the region, determining their waste content and characterising the waste of the foods. The research is limited to the volume and composition of the biogas yield and does not extend to the bio-chemical analysis of the reactants.

1.4 Structure of Thesis

The thesis consists of six chapters which are summarised below:

The **Introduction** is the first chapter and gives the background to the research. The chapter deals with a summary of what the research entails, including its aims and objective. It closes with the motivation for the research and the potential contributions of the study.

The second chapter is the **Anaerobic Digestion of Niger Delta Food Waste.** This chapter provides an analysis of the anaerobic digestion process**.** It then proceeds to the Anaerobic Digestion of Water Hyacinth which introduces the aquatic weed water hyacinth with a review on its anaerobic digestion, including pre-treatment, biogas production and digestion kinetics. The chapter then proceeds to identify the common Niger Delta Food Wastes with a comprehensive literature review on studies involving the identified wastes. The chapter closes with an overview of local regulations that policies that would support the implementation of the findings of this study.

The third chapter, **Experimental Methods**, provides detailed description of the experimental methods used in this study. This includes the methods for determining the waste content of the common foods and the food waste characterisation. Methods for the quantification of the food waste will also be discussed. The methods for the design and operation for various bioreactor configurations are presented. A comprehensive description of the BMP tests is presented. The chapter closes with a description of the statistical tools to be employed for results analysis.

The fourth chapter is the **Results and Discussion: Waste Characterisation, Quantification and Energy Potential**. The results of the waste content, nutrient characterisation and energy potential estimations are presented here.

The fifth chapter is the **Results and Discussion: Bioreactor and Bio-Methane Potential Tests**. The results of the testing of the various bioreactor configurations and Bio-Methane Potentials tests are presented and discussed. The results are used to validate the Modified Gompertz model, while the kinetic parameters for the biogas production of food waste are presented.

The sixth and final chapter is the **Conclusion**. The overall outcome of the study is presented here by outlining the research findings. The implications and limitations of the study are listed. The chapter and thesis closes with recommendations for future studies in the research area.

1.5 Contribution of Research

The successful completion of this research study will contribute the following knowledge to the scientific community:

1. Central location for data on the Niger Delta that relates to energy sources, consumption patterns and waste disposal methods.
2. Identification, characterisation, and Bio-Methane Potential of nine common food waste in the Niger Delta region namely: Yam Peels, Cassava Peels, Cocoyam Peels, Plantain Peels, Corn Cobs and Husk, Egusi Shell, Bean Skin, Groundnut Husk and Ugwu Stalk.
3. Design of practical cost effective bio-reactors that can be used to perform standard BMP tests in laboratories of developing nations.
4. Kinetic parameters of the anaerobic digestion of yam peels, cassava peels, cocoyam peels and plantain peels both mono-digested and co-digested with water hyacinth.
5. Effect of co-digesting food waste with water hyacinth on biogas production.
6. High frequency analysis of the methane and carbon dioxide content of biogas for the full duration of an anaerobic digestion test.
7. Overview of Nigerian renewable energy, rural electrification and environmental policies and regulations.

1.6 Chapter Summary

The chapter has presented the background to the research. There has been an overconsumption of natural resources that has led to high levels of pollution and threatens the ability of future generations to meet their energy needs. Nigeria is a major producer of crude oil but struggles to meet its energy needs. 52% of the population have no access to electricity while a

majority of the population relies on traditional biomass to meet their energy demand. Utilisation of renewable energy sources would provide much needed energy and help mitigate the effects of environmental degradation. The Niger Delta is a region in Nigeria with the most need for renewable energy due to the environmental degradation it experiences from crude oil extraction and processing. Additionally the region's environment suffers from water hyacinth infestation and indiscriminate dumping of domestic waste. The expansion of the national grid to the region is also limited due to the watery terrain of the area. Anaerobic digestion, which is a renewable technology, can be utilised to provide clean energy for the region while mitigating the effects of waste dumping and water hyacinth infestation.

The food wastes that will be used as feedstock for the AD process will come from the commonly consumed foods in the region. These include yam, cassava, cocoyam, egusi, beans, groundnut, plantain, corn and ugwu. These foods will undoubtedly generate large volumes of organic waste, which will serve as substrates for the AD process. Due to the limited studies on the biogas potentials of the wastes from these foods, they will need to be characterised and digested to determine their suitability as AD feedstock.

The aim of this research is to determine the biogas potential of common Niger Delta food wastes. The findings will be used to fill the research gap created by lack of quality data on the waste from common Niger Delta foods. The results from the study will provide the nutrient composition and bio-methane potential of those selected food wastes. The next chapter will present an overview of the anaerobic digestion process while providing a literature review of the past AD studies that have been performed on the selected food wastes of the Niger Delta.

Chapter 2 Anaerobic Digestion of Niger Delta Food Waste

In the last chapter, the background, motivation and aims of the thesis were presented. This chapter presents an overview of the anaerobic digestion process. Themes include the digestion stages, feedstock types and pre-treatment methods. Next the water hyacinth is introduced while its potential as an anaerobic digestion feedstock is reviewed. The Niger Delta is then presented and the commonly consumed foods are identified. A literature review of the anaerobic digestion of the wastes from the common foods is performed. The chapter closes with an overview of local renewable energy and environmental regulations and policies.

2.1 Anaerobic Digestion

Anaerobic digestion is the degradation of complex organic compounds leading to the production of biogas. The biogas is a fuel that consists primarily of methane and carbon dioxide. It serves as an energy carrier and is combusted to provide energy in the form of heat and/or electricity. The process is facilitated by microorganisms in an oxygen free environment. A by-product of the AD process is the digestate which is a nutrient rich material that may be used as a soil conditioner on farmlands.

2.1.1 Stages of Anaerobic Digestion

Anaerobic digestion proceeds through four distinct stages namely Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. Each of the phases has its own specific reactants, products and microbiology.

Hydrolysis

The first stage in anaerobic digestion is Hydrolysis. This phase involves the breakdown of the complex organic compounds into simpler chains to facilitate consumption by microbes. Carbohydrates, proteins and fats are broken down into sugars, amino acids and fatty acids respectively. This is accomplished by the enzymes amylases, proteases, and lipases. The chemicals are produced from their corresponding hydrolytic bacteria. The results of Yang et al. (2015) showed that carbohydrates are more efficiently degraded than protein in this stage. A reaction of the breakdown of carbohydrate into glucose molecule is given below:

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6$$

Some complex feedstocks require pre-treatment prior to the hydrolysis stage due to the complex nature of their composition. This will be explored further in subsequent sections.

Acidogenesis

In the second stage, the acidogenic microbes transform the sugars and amino acids from the first stage into organic fatty acids such as propanoic, butanoic and acetic acid. Other products are alcohols, hydrogen, carbon dioxide and ammonia.

Acetogenesis
In the third stage, the acetogenic microbes convert the acidogenic products into acetic acid, carbon dioxide and hydrogen.

Methanogenesis
The fourth and final stage is called Methanogenesis. In this stage, methanogenic microorganisms convert the products from the previous stages into methane and carbon dioxide. The process is facilitated by either acetotrophic or hydrogenotrophic methanogens.

2.1.2 Feedstock

Feedstock is the substrate that is fed into the anaerobic digester for biochemical degradation. The raw material is composed primarily of organic matter and some traces of inorganic contaminants. The organic content consists of nutrients which are ultimately converted to biogas. Certain feedstocks contain nutrients which are in complex forms and are not accessible to the AD microbes. Such nutrients would have to be broken down into simple forms that can be digested by the microorganisms. This is achieved through a process called Pre-treatment which may also remove the inorganic impurities of the feedstock.

The bioenergy yield of a feedstock will depend on various criteria such as nutrient content, AD process parameters and purity of feedstock. A wide range of organic matter has been digested to produce biogas. Examples of various feedstocks that have been used in the AD process are presented in Appendix 11.

2.1.3 Pre-treatment of Feedstock

Feedstock for anaerobic digestion consists of both basic and complex organic molecules. The simple molecules can be consumed directly by the AD microbes while the complicated molecules like lignin have to be broken down into simpler units for microbial digestion by a pre-treatment process. The aim of this process is to increase the biogas yield and the conversion rate of the bio-reaction. AD pre-treatment can be categorised into three distinct processes namely: physical, chemical and biological pre-treatment. The **Physical Pre-treatment** includes processes that have a physical effect on the feedstock. **Comminution** reduces the particle size of lignocellulosic biomass by grinding and milling; **Ultrasonic Treatment** uses ultrasound frequencies to disrupt the cell walls of microorganisms: **Electrokinetic Disintegration** uses electric fields to disrupt the ionic bonds that cause

microbes to form flocs. **Chemical Pre-treatment** is the use of chemicals to break down the polymer chains of complex organic feedstock in order to improve microbial accessibility. Common groups of chemicals used are alkalis, acids and oxidatives. **Alkali Pre-treatment** uses alkalis to make the hemicellulose in lignocellulosic materials to be more accessible to the enzymes in the hydrolysis stage, and the solubilisation of lignin into cellulose and hemicellulose; **Acidic Pre-treatment** uses acids to break down the complex molecules of difficult to digest feedstock; **Oxidative Pre-treatment** using oxidizing agents to attack the aromatic rings of lignin leading to its solubilisation. **Biological Pre-treatment** uses microbes to break down complex polymers. This includes **Fungal Pre-treatment,** which uses the digestive enzymes of fungi to decompose and degrade feedstock while **Enzymatic Pre-treatment** uses biological catalysts that are secreted by microbes to break down polymers such as lignocellulosic chains.

Combined Pre-treatment utilises two or more methods to pre-treat a feedstock. These include: **Steam Explosion** which involves heating a substance under pressure leading to an explosion that causes cells of lignocellulosic feedstock to lose their structure; **Extrusion** which involves grinding the feedstock under high pressure leading to disintegration of cell structure; **Thermochemical** which uses both high temperature and chemical substances to break down the complex chains of feedstock.

2.1.4 Inhibition of the Anaerobic Digestion Process

Anaerobic Digestion may suffer from inhibition that can reduce the efficiency of the process or lead to outright digestion failure. Compounds like Ammonia and Hydrogen Sulphide are produced from the degradation of proteins and sulphur compounds respectively. High concentrations of Ammonia adversely affect the cells of AD microbes, while Hydrogen Sulphide precipitates metallic ions, leading to a deficiency of metallic ions for microbes that require such ions. Other compounds like oxygen are toxic to strictly anaerobic microbes. Light metal ions form salts in water leading cells to lose water via osmotic pressure. Heavy metal ions bind to other groups on protein molecules or replace naturally occurring metals in enzyme prosthetic groups, disrupting enzyme structure and functioning. Long chain fatty acids inhibit the function of AD microbes by interfering with the transport and protection functions of their cell walls. Additionally chemicals like Chlorophenols and Halogenated Aliphatics are toxic to microbes by disrupting the energy transduction of their cells and affecting methanogenesis by inhibiting substrate consumption and methane formation

2.1.5 Biogas upgrading and applications

Biogas is the gaseous product of the Anaerobic Digestion process. It consists of a mixture of gases, mainly Methane (CH_4) and Carbon Dioxide

(CO_2). Other gases present in lesser quantities are Nitrogen, Hydrogen, Oxygen, Hydrogen Sulphide (H_2S) and Ammonia (NH_4).

In certain applications, there is a need for the biogas to be purified, which involves cleaning and upgrading the gas before utilisation. The cleaning of the biogas also removes impurities that damage the equipment that combust, compress and store the gas. Table 2-1 presents the common impurities found in biogas and their effects on the AD system as identified by Deublein and Steinhauser (2011) and Ryckebosch et al. (2011).

Table 2–1 Impurities of biogas and their effects on the AD process
Note: Data from (Deublein and Steinhauser, 2011; Ryckebosche et al., 2011)

Impurity	Content (%)	Effect
CO_2	25-50	Lowers calorific value of biogas. Causes corrosion via carbonic acid if gas is wet. Increases anti-knock properties of engines. Damages alkali fuel cells.
H_2S	0-0.5	Causes corrosion in piping systems, compressors, gas storage tanks, and engines. After combustion forms SO_2 and SO_3 which are more toxic than H_2S, and react with water to cause corrosion. Spoils catalysts.
NH_3	0-0.05	Causes corrosion when dissolved in water. Increases anti-knock properties of engines.
Water Vapour	1-5	Causes corrosion in equipment in reactions with CO_2, H_2S and NH3. Accumulation of water in pipes. Condensation and/or freezing under high pressure, which damages nozzles, instruments and plants.
Dust	> 5 µm	Deposits of dust cause clogging in nozzles, compressors, gas storage tanks and fuel cells.
N_2	0-5	Lowers the calorific value of biogas. Increases the anti-knock properties of engines.
O_2	0-1	Combines with other biogas contents to produce explosive mixtures.
Cl	0-100 (mg/m^3)	Causes corrosion in combustion engines
Fl	0-100 (mg/m^3)	Causes corrosion in combustion engines

Upgrading is performed to increase the calorific value of the biogas resulting in more energy output per unit volume of gas. This process may be referred to as the conversion of biogas to bio-methane. Upgrading methods include high pressure water scrubbing, polyethylene glycol scrubbing, chemical absorption, pressure swing absorption, membrane separation, biological methane separation and cryogenic separation.

Biogas as an energy carrier has various applications that are limited by the purity of the biogas. These applications include direct combustion to produce energy, injection into the natural gas grid and fuel for combined heat and power (CHP) systems, gas turbines, fuel cells and vehicles.

2.1.6 Anaerobic Digestion Benefits and Applications

- The AD process utilises biomass, which is inexhaustible. Such biomass includes organic wastes which would have ended up in landfills adding to environmental degradation.
- AD provides a clean energy source as an alternative to conventional fossil fuels which pollute the environment.
- The process reduces greenhouse gas emissions by the utilisation of a closed carbon cycle.
- AD may provide a dual source of revenue from both the biogas and the digestate that can be sold to farmers.
- The AD process is robust and can use different types of feedstock.
- The digestate produced is rich in nutrients, making it suitable for crops. This is an advantage over industrial fertilisers which consist of chemicals.
- A completed AD process reduces foul smelling compounds. This makes the digestate a better option to manure that gives out odours when applied to farmlands.
- AD eliminates a large amount of harmful disease carrying pathogens that are found in organic waste. These pathogens would have been disposed in the environment and become harmful to humans or animals.

2.1.7 Anaerobic Co-Digestion

Anaerobic Co-digestion is the digestion of a mixture of feedstock. The substrates have complementary characteristics and their combination stabilises the digestion process by providing missing nutrients. This synergy results in an increase in gas production. Mata-Alvarez et al. (2014) concluded that co-digestion of various substrates produces more methane yield than if the individual substrates were digested separately, and the methane they each produced is added up. Braun and Wellinger, (2003) determined that co-digestion is commonly applied in wet, single step continuously stirred reactors.

Anaerobic co-digestion benefits that cover both technological and economical areas were identified by Braun and Wellinger (2003), Esposito et al. (2012) and Mata-Alvarez et al. (2014). They are listed below:

- Improved nutrient balance.
- Homogenisation of particulates.
- Increased and stable production of biogas.
- Production of nutrient balanced digestate.
- Dilution of inhibitors and toxic compounds.
- Balanced moisture content.
- Stable pH and improved buffer capacity.
- Widening the range of bacterial strains in the digester.

- High organic loads.
- Steady supply of feedstock.
- Improved C/N ratio.

2.1.8 Models of Anaerobic Digestion

1. Models for Theoretical Biogas Production

These are models that are used to determine the potential biogas yield of a substrate based on its chemical composition or nutrient characteristics. The models are time independent meaning they do not allow for dynamic investigations. They work on the assumption that all the organic content will be converted to biogas.

Buswell Equation

The Buswell Equation (Buswell and Mueller, 1952) addresses the chemical mechanisms by which methane is produced in nature. Buswell and Mueller believed the model could be used to calculate 95-100% of yields. The equation represented in (1) uses the amount of Carbon, Hydrogen, Oxygen and H_2O in a sample to determine its potential methane and carbon dioxide yield.

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} + \frac{c}{4}\right) CH_4 + \left(\frac{a}{2} + \frac{b}{8} + \frac{c}{4}\right) CO_2 \quad (1)$$

Once the elemental content is known, the values are inputted into the equation to obtain the theoretical yields.

Boyle Equation

The Boyle equation is an improvement on the Buswell equation. It adds the Nitrogen and Sulphur content to the equation. In response the amount of ammonia and hydrogen sulphide in the biogas is provided. The equation is presented in (2):

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3{\cdot}d}{4} + \frac{e}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} + \frac{c}{4} + \frac{3{\cdot}d}{8} + \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} + \frac{b}{8} + \frac{c}{4} + \frac{3{\cdot}d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \quad (2)$$

Baserga Equation

The Baserga Equation (Baserga, 1998) uses the nutrient composition of a substrate to determine its bio-methane potential. The nutrients used for the calculations are Crude Fibre, Crude Protein, and Crude Oil. Ash and moisture content also have to be determined. The Nitrogen Free Extracts (NFEs) and Volatile Solid content are calculated using the previously mentioned nutrients. Other parameters required for the use of the equation are the digestibility factors and the gas yield conversion values of the nutrients. The complete set of equations, digestibility factors and gas yield conversions for the model are presented in Appendix 1.

Methane Energy Value Model

The Methane Energy Value Model shown in (3) uses regression models to estimate the methane yields of energy crops based on their nutrient composition. These nutrients are the Crude Fibre (XF), Crude Protein (XP), Crude Fat (XL) and Nitrogen Free Extracts (XX) (Amon et al., 2007a). The model uses the following Specific Methane Yields:

Specific Methane Yield of Carbohydrates (C_rF and NFE) =395 l/kg VS

Specific Methane Yield of Crude Protein =490 l/kg VS

Specific Methane Yield of Crude Fat =850 l/kg VS

$$MEV = x_1 \cdot XP + x_2 \cdot XL + x_3 \cdot XF + x_4 \cdot XX \quad (3)$$

All nutrient contents are in % DM while each *x* represents a coefficient of regression.

2. Growth Kinetic Models

These models utilise reaction kinetics to predict biogas production rates. Their focus is on the rate of consumption of substrates, the population growth rate of the microbes and the rate of production of biogas. The variation in the growth rate of the microorganisms translates to the variation in the rate of biogas production. Michaelis and Menten, two German biochemist derived the basis for modelling the kinetics of bacterial growth in 1913. Their model showed that substrate concentration determined enzyme activity, which can be related to bacterial growth (Kythreotou et al., 2014).

Monod Kinetic Model

Monod (1949) proposed that the specific growth rate of bacteria is inversely proportional to the substrate concentration. Hence the specific growth rate rapidly increases for low concentration of substrates, while it slowly increases for high concentrations, until a saturation of bacteria is achieved. This was based on the implicit assumption that all the bacteria are capable of division and is a fine assumption if homogenous bacterial populations are considered. Monod's Kinetic model is shown in equation (4) with the various parameters defined below.

$$\mu = \mu_{max} \cdot \frac{S}{K_S + S} \quad (4)$$

μ Specific Growth Rate (day^{-1})
μ_{max} Maximum Specific Growth Rate (day^{-1})
K_s Monod Constant (mol/litre).
S Concentration of substrate (mol/litre)

Gerber and Span (2008) concluded that the accuracy of the model is high when used for pure of homogenous cultures, in contrast to heterogeneous or complex ones.

Contois Kinetic Model

Contois (1959) showed that the specific growth rate of microorganisms is a function of their population density and the concentration of the substrate. The Contois Kinetic Model is shown in equation (5). Contois believed that the model could be used to determine bacterial growth in both batch and continuous cultures of bacteria.

$$\mu = \mu_{max} \cdot \frac{S}{K_c \cdot X + S} = \mu_{max} \cdot \frac{1}{\frac{K_c \cdot X}{S} + 1} \quad (5)$$

μ Specific Growth Rate (day^{-1})
μ_{max} Maximum Specific Growth Rate (day^{-1})
K_c Contois Kinetic Constant
S Concentration of substrate (mol/litre).
X Microorganism Concentration (mol/litre).

Contois conducted experiments using *Aerobacter aerogenes* in chemically defined media and was able to show the applicability of the model in AD analysis.

Chen and Hashimoto Kinetic Model

Chen and Hashimoto (1980) used the Contois Model as a foundation to build a model that takes into account the non-biodegradable content of the substrate, which was represented by a refractory co-efficient. The model is presented in equation (6). The kinetic parameters and refractory co-efficient were proved to be independent of the substrate concentration. In addition it was shown that temperature variation cause the kinetic parameters to vary while the refractory co-efficient are constant.

$$\mu = \mu_{max} \cdot \frac{\frac{S}{S_i}}{K + \frac{(1-K) \cdot S}{S_i}} \quad (6)$$

μ Specific Growth Rate (day^{-1})
μ_{max} Maximum Specific Growth Rate (day^{-1})
K Chen and Hashimoto Kinetic Constant
S Concentration of substrate (mol/litre).
S_i Initial Substrate Concentration (mol/litre).

These are the basic kinetic models upon which other studies base their models. Other models address the influence of inhibitors, pH, temperature and gas-liquid equilibrium on bacterial growth.

3. Modified Gompertz Equation

The Modified Gompertz Equation (Zwietering et al., 1990) is a model that is used to simulate the cumulative biogas production in AD tests. The model shown in (7) is derived from the Gompertz equation, which assumes that the biogas production rate is a function of the growth rate of microbes in the digester. This equation is widely used for analysing the kinetic constants in biogas production from batch systems.

$$M = P \times \exp\left\{-\exp\left[\frac{R_m \times e}{P}(\lambda - t) + 1\right]\right\} \quad (7)$$

M	Cumulative Biogas Production (m^3/kg VS)
λ	Lag Phase (days)
t	Digestion Period (days)
R_m	Maximum Biogas Production Rate (m^3/kg VS/day)
P	Biogas Production Potential (m^3/kg VS)
e	2.718282

The model is commonly utilised in the analysis of anaerobic digestion of complex and co-digested substrates.

4 IWA Anaerobic Digestion Model No. 1

The Anaerobic Digestion Model No.1 (Batstone et al., 2002) is a generalised anaerobic digestion model that was developed by the Anaerobic Digestion Modelling Task Group in 2002. It is considered one of the most comprehensive AD models. It was created to overcome the restrictions of previous models, mainly their narrow application because of their over-specificity (Yu et al., 2013). The major limitation of the model is its complexity, which creates a need for many input parameters. This leads to multiple stoichiometric and kinetic equations of which their parameter identification and manipulation can be demanding. The model also assumes a fixed volume and completely mixed system. Such mixing is difficult to achieve in large scale digesters, hence the models predictive accuracy is limited (Yu et al., 2013).

2.2 Anaerobic Digestion of Water Hyacinth

Water hyacinth also known as *Eichhornia crassipes* is an aquatic plant/weed that originated from the Amazon Basin. The plants main habitat is the fresh waters of warm tropical climates. The weed is a free-floating perennial plant with broad leaves, bulbous stalks, free hanging roots and lily-like flowers. Its height can range from a few inches to more than a meter. Known as one of the fastest growing plants, it reproduces both sexually by seeds and asexually and can double its population within 6-18 days. The plant flowers in two weeks and releases more than 3000 seeds per year into the water which can live up to 20 years (Scalera et al., 2012). The seeds sink to the bottom of the water body and remain dormant, germinating when conditions are favourable. The plant can have a density of up to 200 tonnes per acre. The plant causes numerous socio-economic problems including flooding, blockage of irrigation, water pipes and hydropower systems, water transport disruption, home to dangerous wild animals and disease carrying vectors, destruction of biodiversity and increase in evapotranspiration. The plant also has some beneficial uses such as being a feedstock for the anaerobic digestion process and used as an environmental remediation agent.

Water hyacinth is a storehouse of energy and can be digested to produce biogas. Studies have been carried out on the anaerobic digestion of water hyacinth in a bid to develop the most efficient method of digesting the plant. These include studies on pre-treatment methods, digester configurations, and co-substrates. Plants such as water hyacinth can be degraded to give high gas yields; hence their digestion can reduce excessive weed growth in addition to providing energy. Furthermore studies have even been performed on extracting the VFAs from the water hyacinth using inexpensive materials (Ganesh et al., 2005).

2.2.1 Pre-treatment

Water hyacinth consists largely of water in addition to trapped air that gives it buoyancy. Digesting the fresh plant leads to a low energy output per volume. Furthermore the trapped air in the plant has the potential to make it float and clog digesters. Additionally water hyacinth consists of cellulose, hemicellulose and lignin. These complex compounds are not easily accessible to AD microbes leading to incomplete digestion or longer retention times. This creates a need for pre-treatment in order to improve the digestibility of the plant and its energy output.

Physical Pre-treatment

This pre-treatment method involves mechanically processing the plant to affect its digestibility. Physical pre-treatment of WH involves drying the plant and then grinding or milling it to reduce its particle size and increase the surface area. Verma et al. (2007) showed that WH dried at $60^{O}C$ for 48 hours, with particle sizes of 5 mm had a higher biogas yield compared to particles of 2 mm, 10 mm and 20 mm. Furthermore Moorhead and Nordstedt (1993) investigated the biogas potential of frozen and chopped water hyacinth. The results indicated that particle sizes of 6.4 mm produced the highest biogas yield, followed by the 1.6 mm and then the 12 mm. These two studies conclude that the particle size should not be too large or too small for efficient digestion. However dried water hyacinth was shown to produce less biogas than the fresh sample by O'Sullivan et al. (2010) and Chanakya et al. (1993). This contradicts the results of Patil et al. (2011) which indicated that dried water hyacinth produces more biogas than the fresh plant. In a related study comparing the biogas yield of fresh and frozen-thawed water hyacinth, the results of Chynoweth et al. (1982) showed that there was no difference in gas yield of both samples. The trapped air in water hyacinth may be removed by chopping the plant into smaller pieces. Patil et al. (2011) improved the biogas yield of water hyacinth by chopping the plant into 2 cm pieces, drying and grinding into fine particles. Practically a balance would have to be obtained between pre-treatment method, transportation of the plant and digester configuration. In larger quantities, the water hyacinth can be sun dried. The high temperatures of the tropical regions make this method

effective and cost free. The major setback would be finding enough space to dry the high amounts of the plant.

Chemical Pre-treatment

Chemicals can be used to destroy the lignin in water hyacinth leading to access of cellulose and hemicellulose which can then be broken down into sugars that can be accessed by AD microbes. Patil et al. (2011) examined the effect of NaOH pre-treatment on water hyacinth. The results showed that the treatment led to a higher yield of biogas. Furthermore Cheng et al. (2010) tested the effect of various concentrations of NaOH on the pre-treatment of water hyacinth. The results showed that water hyacinth pre-treated with NaOH at 0.5% wt produced the highest methane yield. Advancing that method, water hyacinth was soaked in NaOH, microwave heated and then subjected to hydrolysing enzymes. This process destroyed the lignin structure and disrupted the crystalline cellulose. The use of ionic liquids for pre-treatment of water hyacinth by Gao et al. (2013) led to a removal of 49.2% lignin and an increase in biogas yield by 97.6%. The study also provided a novel method of successfully recovering the ionic liquid for re-use. Dilute H_2SO_4 can also be used to increase the reducing sugars in water hyacinth leading to a higher biogas output (Cheng et al., 2013). The process increased the production of glucose by the disruption of the lignocellulosic structure of water hyacinth.

Biological Pre-treatment

Biological pre-treatment involves the use of organisms to break down the complex structures of water hyacinth for accessibility by the anaerobic microbes. The biological pre-treatment of water hyacinth using two mushroom species of *Pleurotus spp*. was performed by Mukherjee and Nandi (2004). The results showed that *P. florida* was more effective than *P. citrinopileatus* in the delignification of water hyacinth.

Overall there has to be a balance between cost of pre-treatment and its practicality in remote rural locations. Gunnarsson and Peterson (2007) suggested that developing countries should not utilise expensive pre-treatment methods, but rather longer residence times for feedstock.

2.2.2 Digestion and Gas production

The gas production potential of water hyacinth has been studied by various researchers. The results from the studies have shown different operational conditions that improve the biogas yield of the plant. Madamwar and Patel (1990) determined that maximum methane yields can be obtained from water hyacinth at a retention time of 7-9 days, temperature of $35^{O}C$, TS of 7-9% (w/v) and S:I ratio of 7:3 (w/w). The results of Chuang et al. (2011) showed that the optimum temperature and concentration for water hyacinth digestion

was 62.5^{O}C and 47.8g/L respectively. Verma et al. (2007) indicated that a S:I ratio of 1:1 for water hyacinth produced the highest biogas yields while a ratio of 1:0.5 produced the least biogas. The study also observed that the ratios of 1:2 and 1:3 produced biogas with a lower methane content compared to ratios of 1:1 and 1:0.5.

Among the various parts of the water hyacinth, Shiralipour and Smith (1984) showed that the shoots produced the highest methane yields of 0.32 m^3/kg VS while the roots had a lower gas production of 0.18 m^3/kg VS. Cheng et al. (2010) took the study a step further by comparing the methane yields of the leaves, stem and roots of water hyacinth. The results showed that the leaves, which contained low lignin/ash and high cellulose/hemicellulose, had the highest methane yield. The stems had the next highest yield while the roots, having a high ash content, had the lowest methane production. The study of Shiralipour and Smith (1984) showed that the addition of nitrogen to water hyacinth growth media significantly increases its methane yield. This contradicts the results of Moorhead and Nordstedt (1993) which showed that high nitrogen water hyacinth produced lower biogas yields when compared to the low nitrogen water hyacinth. The difference in findings could result from different concentrations of nitrogen utilised.

Geeta et al. (1990) were able to increase the biogas production from water hyacinth by up to 54% when supplemented with nickel at 2.5 ppm. This is supported by Patel et al. (1993) which showed that the addition of metallic salts to water hyacinth increased gas production by up to 60%. The study by Singhal and Rai (2003) indicated that water hyacinth grown in metal-rich effluents of paper and pulp mills and highly acidic effluents of distilleries produced significantly more biogas than water hyacinth grown in clean water. Furthermore Verma et al. (2007) showed that water hyacinth grown in effluent from brass and electroplating industries produced significantly more biogas than water hyacinth grown in unpolluted water. Studies have also been conducted to find alternative methods of extracting the nutrients from water hyacinth. Ganesh et al. (2005) developed a cheap method of extracting VFAs from water hyacinth using diluted cow dung. The extracted VFAs were used as liquid feedstock in a digester. The process eliminated the bulky and indigestible fibres that would otherwise increase digester volume with lower energy outputs. The spent water hyacinth can then be processed and used on crops.

2.2.3 Kinetics of the Anaerobic Digestion of water hyacinth

The Modified Gompertz Model is commonly used to determine the kinetic parameters of the biogas production rates of complex substrates including water hyacinth. A review of literature provided some of the following examples. Adiga et al. (2012) used the model for a comparative analysis of the biogas yields of water hyacinth, poultry litter, cow manure and primary

sludge. Chuang et al. (2011) used the model for tests on the effects of substrate concentration and incubation temperature of water hyacinth. Su et al., (2010) used the model to assess the bio-hydrogen production from the dark and photo fermentation of water hyacinth. Lay et al. (2013) analysed the co-digestion of water hyacinth and beverage wastewater using the model. Cai et al. (2012) examined the effect of nickel ions on the bio-methane production of water hyacinth. Rai et al., (2011) used the model to determine the kinetics of the co-digestion of water hyacinth and primary sludge. Cheng et al., (2013) used the model to determine the production kinetics of microwave assisted treatment of water hyacinth. Patil et al., (2011) determined the effects of water hyacinth pre-treatment using the model.

2.2.4 Limitations of Water Hyacinth Digestion

1. Water hyacinth is filled with air leading to buoyancy. This causes the raw plant to float and clog digesters. Physical pre-treatment releases the trapped air from the plant. Alternatively the VFAs can be extracted from the water hyacinth and used directly in the digester.

2. Water hyacinth consists mainly of water at approximately 95% leading to a low nutrient content and low energy output. Drying and co-digestion mitigate this problem.

3. The presence of lignocellulosic material makes the plant hard to digest. A variety of pre-treatment methods break down the lignocellulosic material, making the nutrients readily available for digestion.

2.2.5 Anaerobic Co-Digestion of Water Hyacinth with various Feedstock

Co-digesting water hyacinth with other feedstock improves digester performance by balancing the C/N ratio and also presenting readily available nutrients for the microbes while the recalcitrant lignocellulosic materials of water hyacinth are slowly broken down. O'Sulllivan et al. (2010) showed that co-digesting manure with water hyacinth produced a higher biogas yield compared to digesting manure alone. In a similar study, Ganesh et al. (2005) showed that digesting cow manure with the VFAs from water hyacinth, produced 22% more biogas. Patil et al. (2011) showed that water hyacinth co-digested with poultry waste produced more biogas than when water hyacinth was mono-digested. Momoh and Nwaogazie (2008) co-digested waste paper with water hyacinth leading to an increase its biogas yield. Cassava peel co-digested with water hyacinth had an increased biogas yield when compared to individual digestion of each separate substrate (Asikong et al., 2012). The review shows that water hyacinth is commonly co-digested with animal manures and has a positive effect on biogas yields. There is limited literature on the effect of co-digesting water hyacinth with food wastes or crop residues leading to a research gap.

2.3 Niger Delta Food Waste

The Niger Delta is an oil rich region in the southernmost coast of Nigeria. The region has an area of 112,110 square kilometres and represents 12% of Nigeria's total surface area (NDDC, 2006). The region is densely populated with a total population of 31,277,901 with 6,776,297 households (NPC, 2006). The population is projected to reach 45,715,000 by the year 2020 (NDDC, 2006). Figure 2-1 presents the Niger Delta location relative to Nigeria and Africa.

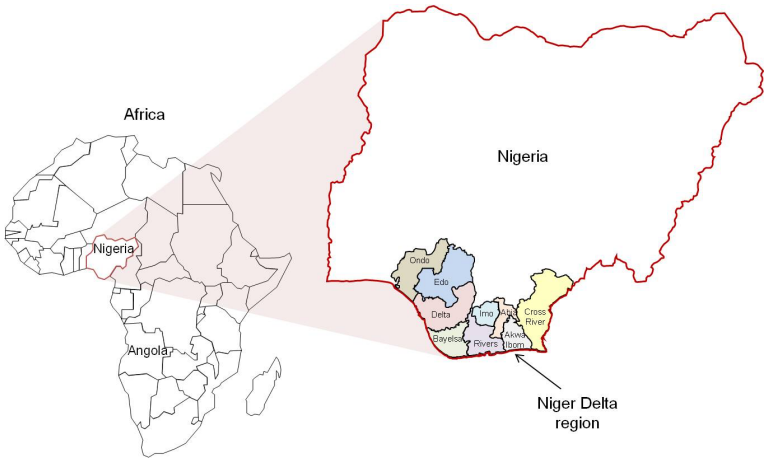


Figure 2–1 Location of Niger Delta (Flemming, 2015)

The predominant occupation of the rural folk are farming and fishing (NDDC, 2006). The region is a sedimentary basin and one of the largest wetlands in the world. The climate ranges from equatorial to tropical and is both humid and hot (UNDP, 2006). The amount of rainfall can vary widely between coastal and northern towns. Mean annual rainfall can reach up to 4,000 mm in coastal towns while the temperature ranges from 23.6 to 31.9^{O}C (NBS 2012b). Energy for cooking in the region is traditional biomass, specifically firewood which generates greenhouse gases and contributes to deforestation and land erosion. This has severe consequences for a region whose land area is already occupied by water bodies. For electrical energy, the Niger Delta is mainly dependent on the national grid for its power supply. The rural communities have limited power as a result of the difficulty in extended the electric grid to riverine areas. 80.3 % of the population are dependant on the national grid (NBS, 2012a). The region suffers environmental degradation from oil spills, gas flaring, Water Hyacinth infestation, inappropriate waste disposal practices, wide scale burning of traditional biomass, deforestation and coastal erosion.

2.3.1 Niger Delta Foods

The food consumption and expenditure patterns of the Niger Delta have been analysed to determine the commonly consumed foods in the region. Ene-Obong et al. (2013) identified commonly consumed foods in different

regions of Nigeria with root tubers being the most commonly consumed foods in the Niger Delta. The study is supported by NBS (2012a) whose results show that the local population spent the highest proportion of their expenditures on tubers and plantain. Furthermore the NDDC (2006) identified cassava and yam as the most common grown crops in the region. The results indicate that yam, cassava, cocoyam and plantain are the most commonly consumed foods in the region.

This section presents nine locally consumed Niger Delta foods. A brief description of each food is presented including their local preparation methods. Their individual annual production yields are presented from the FAOSTAT (2015) database. The nine foods are pictured in Figure 2-2.

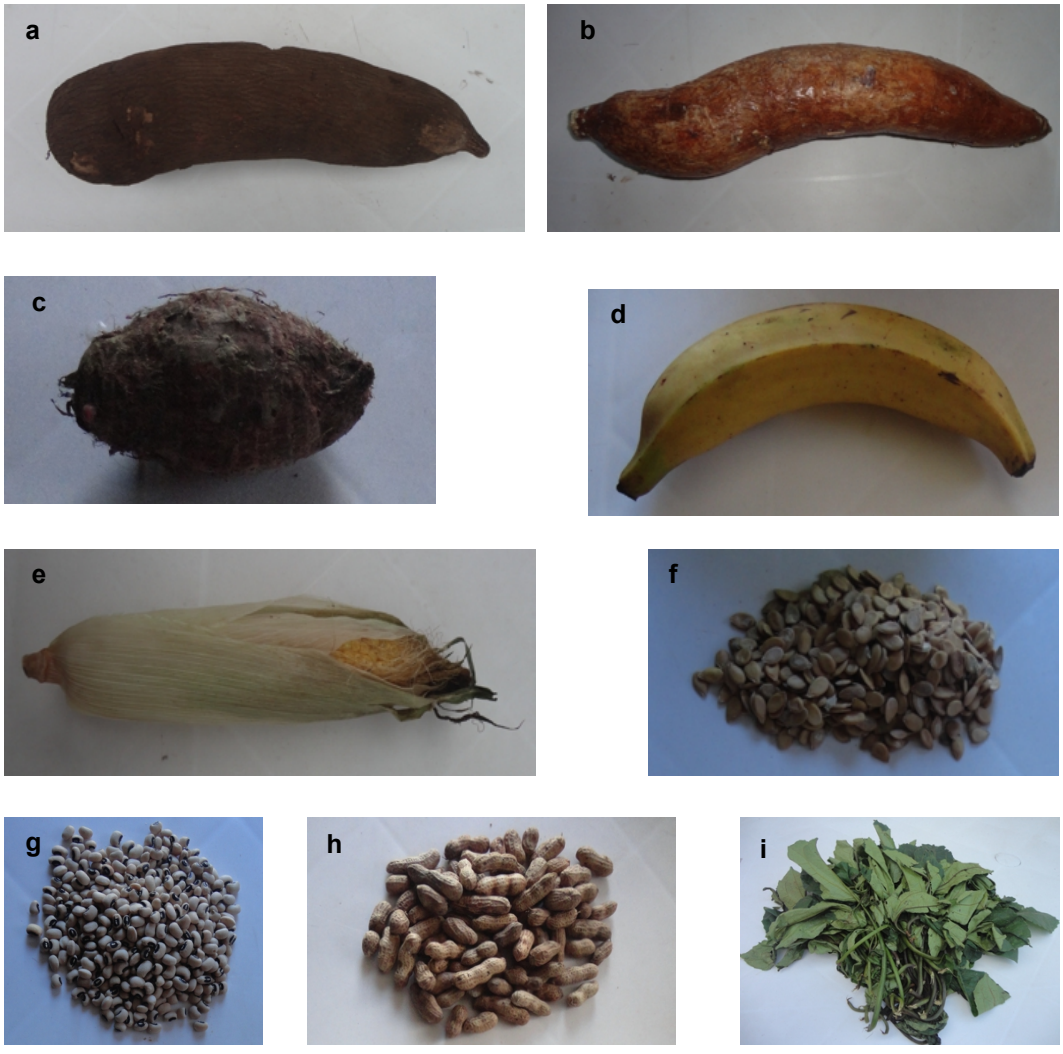


Figure 2–2 Common Niger Delta Foods (a) Yam (b) Cassava (c) Cocoyam (d) Plantain (e) Corn (f) Egusi (g) Beans (h) Groundnut (i) Ugwu

1. Yam (*Dioscorea rotundata*)

The Yam tuber is a perennial herbaceous vine that has a large starchy tuber rich in carbohydrates. The tuber requires a hot humid climate to thrive. Growth takes place underground and takes 6-10 months to reach maturity.

Nigeria is the largest producer of Yam with annual production estimated at 40,500,000 tonnes. Yam is cooked by boiling, pounding, roasting, or frying. The basic method of preparing the food item is by peeling the outer skin and consuming the inner edible flesh. The waste material from yam is “Yam Peel” (YP).

2. Cassava (*Manihot esculenta*)

Cassava is a tuber of the spurge family of plants. The woody crop thrives in tropical climates and has an edible tuber rich in carbohydrates. The plant naturally contains cyanogenic glucosides which are extremely toxic; hence the plant has to be properly processed before consumption. Nigeria is the largest producer of Cassava with an annual production of 53,000,000 tonnes. Cassava is pre-processed by peeling the tuber and soaking it in water for a few days and allowing it to ferment. This detoxifies the plant, making it safe for consumption. After that the tuber is either boiled or pounded. Another method of processing the crop is by peeling, washing and then grinding it into a mash which is then placed in a porous bag to allow the excess moisture and starch to seep away. The resultant dry product is then sieved and fried to produce a locally consumed flour called “garri”. The waste material from the peeling of cassava is “Cassava Peel” (CP).

3. Cocoyam/Taro (*Colocasia esculenta*)

The cocoyam tuber is the storage stem of a tropical perennial plant that stores its food reserves in a bulbotuber or corm. The growth period is 7-10 months. Nigeria is the largest producer of cocoyam with annual production at 3,500,000 tonnes. The consumed part of the plant in Nigeria is the storage stem. The crop is prepared by peeling the outer skin and then boiling, frying or roasting the edible content. It is also used as a soup thickener. The waste from this tuber is the “Cocoyam Peel” (CoP).

4. Plantain (*Musa paradisiaca*)

Plantain is an herbaceous perennial fruit that is commonly confused with bananas. When comparing the two, the plantains are longer, have thicker skin and higher starch content. They grow best in tropical climates and require light for proper development. The plant grows in hanging clusters from trees. Nigeria has an annual production capacity of 2,780,000 tonnes of plantain. Plantains have a lower sugar content compared to bananas so they cannot be eaten raw. The fruit is prepared by peeling off the skin and then boiling, frying or roasting the edible part. The waste from the plantain is known as “Plantain Peel” (PP).

5. Corn/Maize (*Zea mays*)

Corn is an annual grass that is one of the most common food crops in the world. The edible part of the plant is found in the “ears” of the crop which

contain kernels enclosed by a husk. Nigeria produces 10,400,000 tonnes of corn annually. Corn is prepared by taking off the outer husk and then boiling or roasting the ear. Alternatively, the grains are stripped off the cob and ground into flour. The wastes produced by the corn are both the inner “Corn Cob” and the outer “Corn Husk” (CCH).

6. Egusi/Melon Seed (*Citrullus colocynthis*)

Egusi is the seed of a melon *citrullus colocynthis*, not to be confused with the watermelon *citrullus lanatus*. The seeds are the consumed part of the melon whose flesh is bitter, dry and non-edible. Egusi can be harvested year round and are dried immediately they are removed from the melon. In that form they can be stored for long periods. Nigeria is the largest producer of melon seed with an annual production capacity of 510,000 tonnes. Egusi is prepared by removing the shell of the seed. This can be accomplished by hand or de-shelling machines. Thereafter the edible content is ground and used to make soups. The waste from the Egusi seed is called the “Egusi Shell” (ES).

7. Beans/Cowpea (*Vigna unguiculata*)

Beans are legumes that have pods containing edible seeds. They thrive well in tropical climates and dry regions courtesy of their long taproots that can access water deep down in soil. The seeds germinate and produce pods in 60 days. It is an important non-animal source of protein. Nigeria is the largest producer of cowpea with an annual production of 2,950,000 tonnes. Beans are prepared in two ways. The first way is by washing the beans and cooking them. This method produces no waste because the whole bean is consumed. The second method of preparation involves washing and soaking the beans in water. This causes the beans to soften which then eases the removal of the outer skin. The remaining inner part is then ground into a paste and fried to produce “*akara*” or boiled to produce “*moi-moi*”. The outer skin that is removed after washing the beans is the waste product of the process and is known as “Bean Skin” (BS).

8. Groundnut/Peanut (*Arachis hypogaea*)

Groundnut is an annual herbaceous plant that thrives well in tropical and sub-tropical climates. It can withstand brief periods of drought. It is considered a grain legume and grows in pods underground. Nigeria is the third largest producer of groundnut with an annual production of 3,000,000 tonnes of groundnut. For consumption the outer shell of the groundnut is cracked open and the nut is taken out and fried, ground or pressed for its oil content. Furthermore, the groundnut can be boiled or roasted with its shell, and then afterwards the nut is taken out and consumed. The waste product from this nut is called “Groundnut Husk” (GH).

9. Ugwu/Fluted Pumpkin Leaves (*Telfairia occidentalis*)

Ugwu is a leaf obtained from the fluted pumpkin vine. The vine is a creeping plant and is commonly planted beside vertical poles which the vines use for support in growing. There is no data on the annual production of the leaf. This might be as a result of the localised consumption of the plant. The leaves are obtained from the stalk of the plant and are extracted by stripping the leaves from the vines and then used as an ingredient in cooking soups. The waste produced from this plant is the "Ugwu Stalk" (US).

2.3.2 Characterisation of Niger Delta Food Waste

The section presents a review on studies that have determined the nutrient characterisation of nine Niger Delta food waste.

1. Yam Peel

Jekayinfa and Omisakin (2005) performed a complete nutrient analysis of yam peels using the American Society for Testing Materials (ASTM) methods. The results showed the crude fibre, protein and fat content to be 2.51%, 3.62% and 5.62%. Makinde and Odokuma (2015) determined the volatile solid content to be 32.9 VS/TS using the Association of Official Agricultural Chemists (AOAC) standard methods of analysis. Fasina (2014) identified the fibre content of yam peel to be 34.84% using the Van Soest analysis for hemicelluloses, cellulose and lignin fractions of the sample.

2. Cassava Peel

Ofoefule and Uzodinma (2009) used AOAC methods to determine the volatile solid and fibre content of cassava peel at 49.63% VS/TS and 32% while fat and protein contents of 0.75% and 8.74% were determined using soxhlet extraction and micro-Kjedhal methods respectively. Aro et al. (2010) performed the proximate analysis of the peels for crude protein (4.2%), nitrogen free extractives (55.5%), ether extracts (3.26%) and crude fibre (29.6%) using AOAC methods. Cuzin et al. (1992) determined only the volatile solid by calcination at $500^{O}C$ to be 90-97% VS/TS. Ezekoye et al., (2011) used AOAC methods to determine the volatile solids to be 89.86% VS/TS while Jekayinfa and Scholz (2013) determined the volatile solid content to be 94.64% VS/TS using German standard methods as described in (Linke and Shelle, 2000). Moshi et al. (2015) determined the volatile solids to be 95.5% VS/TS using National Renewable Energy Laboratory methods and crude protein content of 8.1% using micro-Kjeldahl method.

3. Cocoyam Peel

Adeyosoye et al. (2010) was the only study that determined the nutrient content of cocoyam peels. The study used standard AOAC methods to determine the crude fibre, protein and fat content at 7, 3.83 and 9% respectively.

4. Plantain Peel

Eze and Ezeudu (2012) performed a complete nutrient analysis on plantain peel using the analytical methods recorded by Frazier and Westhoff (1995). Results indicated a volatile solid content of 75.67% VS/TS, crude fibre, protein, fat and NFE contents of 31.96, 3.39, 24.34 and 35.68%. Makinde and Odokuma (2015) determined the volatile solid content of plantain peel using the AOAC official methods of analysis and obtained a result of 35.7% VS/TS. Fasina (2014) determined the fibre content of plantain peel using the Van Soest analysis and obtained a fibre content of 32.32%.

5. Corn Cob and Husk

Eze and Ojike (2012) analysed the nutrient content of corn waste using the standard AOAC methods while the Meynell method was used for the volatile and total solid content. The results presented crude fibre, protein, fat and NFE content of 2.87, 0.41, 0.39 and 70.9%. Jekayinfa and Omisakin (2005) performed a complete proximate analysis of the corn cob using the American Society for Testing Materials (ASTM) methods. Crude fibre, protein and fats content were 16.5, 6.25 and 3.25% respectively.

6. Egusi Shell

The literature showed no characterisation of Egusi shell.

7. Beans Skin

Eze and Ezeudu (2012) did a complete nutrient analysis on bean waste using the analytical methods recorded by Frazier and Westhoff (1995). Volatile solids were 79.86 VS/TS. Crude fibre, protein and fats were 21.25, 11.48, 6.28 and 65.17% respectively.

8. Groundnut Husk

Jekayinfa and Omisakin (2005) determined the nutrient content of the groundnut husk using ASTM methods. Results obtained showed that the crude fibre, protein and fat content were 5.35, 5.23 and 3.42% respectively. Osman et al. (2006) determined the volatile solids using AOAC standard methods and obtained 88.33 VS/TS. The crude fibre, in the form of cellulose, hemicellulose and lignin was determined to be 69.48% using the methods described by Van Soest and Jones (1968).

9. Ugwu Stalk

The literature showed no characterisation of Ugwu Stalk.

2.3.3 Anaerobic Digestion of Niger Delta food waste

This section presents a review of the studies that have been performed on the AD of the nine Niger Delta food waste.

1. Yam Peel (YP)

Biogas production of yam peel and food waste mixtures was investigated by Ojikutu and Osokoya (2014). The results showed that the mixture produced a higher average daily production of 345.7ml, higher than that of yam peel at 149.8ml. The test was not laboratory scale and the operating temperature had a wide range of 30-37^{O}C which would hinder reproducing the experiment. Tests were not replicated, there was no data on the cumulative biogas yields and graphs were of low quality. Makinde and Odokuma (2015) compared the biogas potentials of plantain and yam peels when co-digested with cow dung. The results showed the highest biogas yield of 428 ml was obtained from yam peel and cow dung in the ratio 1:1 while there was no yield from the plantain peels alone. The yam peel to cow dung ratio of 1:3 produced 297 ml of biogas which was lower than yield from the ratio 1:1. The conclusion was that yam peel produces more biogas than plantain peels. Tests were not replicated and there was no data on the temperature of the system, which would make reproducing the experiment difficult. There was also no testing on the methane content of the biogas. The only standard testing on yam peel was performed by Heiske et al. (2015) in Denmark. The study used a Solid State Anaerobic Digestion (SSAD) method that requires low process water to determine the biogas potential of yam peel. The results showed that the SSAD is possible with basic inoculation methods and Yam Peel has a biogas yield of 271 ml CH_4/g VS. The digester was run at 28^{O}C to mimic conditions of digesters operated at ambient temperature in Ghana. Gas composition was analysed using a gas chromatograph while gas volume was measured using an automated metering liquid displacement device. Experiments were performed in triplicates and results were presented in standard format. Other studies on yam peel include Akubuenyi and Odokuma (2013) who co-digested yam peel with various animal wastes and Babatola (2008) who co-digested with various local brewery wastes.

2. Cassava Peel (CP)

Early research of the biogas potential of cassava peel was undertaken by Cuzin et al. (1992). The study showed that cassava peels contain cyanogenic glucosides which release cyanide during digestion and are highly toxic to methanogenic microorganisms. The highly acidic process was tested using a plug flow digester. The results showed that the problem of acidification was solved by localising the acidogenic phase. Gas volume was measured using a flow meter and gas composition was analysed using a gas chromatograph. The cassava peels produced 0.66 m^3/kg VS. Further studies by Cuzin and Labat (1992) analysed methods of reducing cyanide levels during the digestion of cassava peel. The results indicated that the natural detoxification enzymes in the cassava peel can be used to reduce the cyanide content during the AD of cassava peel. The experiment was not on a

laboratory scale so there was no replication of tests. The study didn't provide the biogas yield output of the process.

The biogas potential of digesting cassava peels in different ratios with livestock waste as inoculum was investigated by Adelekan and Bamgboye (2009). The AD system used was a full scale 220 L digester and agitation was accomplished by shaking the vessel twice daily. The results indicated that the S:I ratio of 1:1 produced the highest biogas in all the types of animal waste, and as the S:I ratio increased, the biogas production reduced. Cassava peel and pig waste in the ratio 1:1 produced the highest biogas yield at 35 L/kg TS, while cassava peel and poultry waste in the ratio 4:1 produced the lowest at 9.0 L/kg TS. The system was run without external heating and testing was not replicated. A similar study by Ofoefule and Uzodinma (2009) examined the biogas production from the co-digestion of cassava peels with various animal manures in the S:I ratio of 1:1. The bioreactor was a 50 L galvanised metal digester. The peel were dried for four months with the aim of reducing its toxicity, but the levels of toxicity before and after the four months were not determined. The peels were then soaked in water for a week to allow partial decomposition by aerobic microbes. The results indicated that cassava peel and swine manure had the highest cumulative gas yield at 169.6 l/TMS while the lowest was cassava peel alone with 68.7 l/TMS. The methane content was estimated by a flammability test which cannot provide specific concentrations of the gas. The system had no external heating and was not replicated.

The effect of wood ash on the co-digestion of cassava peel and pig manure was investigated by Adeyanju (2008). The bioreactor was a 2.8 L reagent bottle and gas production was measured using water displacement methods over acidified water. The highest production of biogas was from 200 g of cassava peel co-digested with 200 g of pig manure with wood ash which produced 2345 cm^3 of biogas. The lowest yield was from 400 g of macerated peels which produced 83 cm^3 of biogas. The system was operated at ambient temperatures and tests were not replicated. There was no chemical analysis of the wood ash. In another study, local potash and potassium hydroxide were used by Ofoefule et al. (2010) as additives in the digestion of cassava. The reactor system, cassava peel detoxification and lack of toxicity analysis were the exact same as (Ofoefule and Uzodinma, 2009). Results showed that cassava peel digested with potash produced more biogas than both the untreated cassava peel and the batch with KOH. There was no external temperature control and no indication of the amount of chemicals used for each batch. Biogas production from cassava peels were compared against yields from liquid cassava waste by Eze (2010). The reactor was a large 500 L metal vessel. Gas production was measured by water displacement method using a 25 L gallon. The system had no external

heating, leading to a wide temperature range of 26-36^{O}C. There were no results indicating the biogas yields of the substrates. There was only a conclusion that cyanide does not affect the biogas production of cassava peel, without any evidence to back up the finding.

Jekayinfa and Scholz (2013) analysed the biogas production from cassava, cassava peel, palm kernel cake and palm kernel shells in a German laboratory. Experiments were performed using the standard VDI 4630 method. Tests were undertaken at 35^{O}C in 2 L vessels and replicated. The results showed that cassava peel produced the highest amount of biogas at 0.66 m^3/kg VS. Cassava peels and poultry droppings were digested by Ezekoye et al. (2011). The system used was a polyethylene 0.971 m^3 reactor. Poultry droppings were shown to produce more biogas than cassava peel. The method of comparison of the two yields was not standard because the two tests had different retention times. The system also had no external heating leading to variations in system temperature and tests were not replicated. Biogas yields of cassava peels were compared to those of plantain peels co-digested with cow dung by Igwe, (2014). Substrates were soaked in water for a month prior to digestion. The bioreactor was a 5 L metal digester and tests were conducted under ambient temperatures. The results showed that plantain peel blended with cow dung produced more biogas (72 dm^3) than cassava peels alone (48dm^3). Flammability of the gas was confirmed using a biogas burner which had no way to indicate the methane content. The findings from the test cannot be conclusive because the plantain peels had a source of inoculum from the cow dung which would have an effect on its biogas production. Additionally the reactor had no external heating leading to a wide temperature range of 32-43^{O}C.

The effect of cassava peel pre-treatment on biogas production was tested by Moshi et al. (2015) in Sweden. The reactor system used was a Biogas Endeavour System which consisted of 500 ml glass bioreactors operated at 37^{O}C and performed in replicates. The system was purged with nitrogen to create an anaerobic environment. Agitation was achieved by stirrers at 46 rpm on a 30 sec-on and 120 sec-off intervals and gas analysis was by an integrated sensor. There was a control sample of only the inoculum in order to determine the contribution of inoculum to the biogas output. The study showed that alkali pre-treatment followed by enzyme treatment led to 56% more methane than from the untreated cassava peel. That pre-treatment combination produced the highest biogas yield at 316 - 352 L/kg VS while the untreated samples produced 272 - 292 L/kg VS. Ukpai et al. (2015) studied the effect of temperature on anaerobic digestion of cow dung, cowpea and cassava peel. Biogas composition was measured by an “Orsat Apparatus” without further elaboration. The results showed that 15 kg of cassava peel had a maximum daily biogas production of 6.8L and cumulative

of 95.7L. The tests ran for 30 days with no external heating leading to a wide range of reactor temperature at 20-38^{O}C. The authors concluded that anaerobic microbes thrive best at 37^{O}C with no data from the tests to back up their conclusion.

3. Cocoyam Peel (CoP)

The only study on the biogas potential of cocoyam peel was performed by Adeyosoye et al. (2010). The test was performed at 39^{O}C using only 200 mg of cocoyam peel. The experiment was stopped after 24 hours and showed a yield of 72 ml of biogas. There was no data on biogas composition.

4. Plantain Peel (PP)

Banana and plantain peels were anaerobically digested by Ilori et al. (2007) using a 20 L stainless steel digester. Mixing was by "constant agitation". Biogas was collected using water displacement method over acidified water with no specifications of the acid type or concentration. The results indicated that co-digesting banana and plantain peels produced six times more biogas than digesting plantain peel alone. The system was run for 35 days with no external heating. Eze and Ezeudu (2012) compared the biogas potential of plantain peel, bean skin and other food waste. The system used was a fabricated 0.1 m^3 metallic digester while gas composition was measured using a "dragger X-am 7000". 9 kg of plantain peel produced a lower biogas yield of 44.3 L compared to the 50.4 L for 6 kg of bean skin. The conclusion was that bean skin produced more biogas than plantain peel. The method of comparison was not standard due to the difference in the mass of substrates.

A study of the biogas potential of plantain peel, yam peel and other food waste was performed by Ojikutu and Osokoya (2014). The results showed that 3.3 kg of Plantain peel had the lowest average daily yield of 130.9 ml while 2.2 kg of yam peel had a higher average daily yield at 149.8 ml. There was no indication of the cumulative biogas yield of the samples only poor biogas graphs that could not be analysed. Also the method was faulty because it utilised different masses of the various substrates for a comparative test. Uhuegbu and Onuorah (2014) analysed the biogas production from the co-digestion of plantain peels with cow dung. The samples were ground and soaked overnight in water for partial decomposition by aerobic microbes. The reactor was a 0.3 m^3 mild steel metal digester running at ambient temperatures of 32-42^{O}C. Methane content was verified using a flammability test. The results showed that 2.5 kg of plantain peel produced 8.06 dm^3/kg of biogas. The authors concluded that co-digesting plantain peel with animal wastes improved biogas yields but there was no data on the biogas yield of the plantain peel alone. The tests were also not replicated.

5. Corn Cob and Husk (CCH)

The biogas yields of various corn wastes were analysed by Eze and Ojike (2012). The wastes included maize chaff, stalk and cobs. The reactor was a 0.1 m^3 metallic digester operated under ambient conditions and flammability was confirmed using a biogas stove. Results showed that maize chaff produced the most biogas but the substrate to water ratios were different between samples. The authors confirmed the flammability of the biogas and identified the methane content of 66.2% without mentioning the analysis method. There was no data on the feedstock quantity or type of inoculum utilised.

6. Egusi Shell (ES)

The literature search found no studies on the anaerobic digestion of Egusi shell.

7. Beans Skin (BS)

Ukpai and Nnabuchi (2012) compared the biogas production from bean waste and cassava peel. The reactor was a 45 L metallic digester that operated at ambient temperatures ranging from 22-36^{O}C while gas production was measured by the water displacement method. The flammability of biogas was tested by a biogas burner while the biogas composition was measured using the "Orsat Apparatus". There were no details or explanation of the apparatus. The results showed that bean wastes had a higher biogas production and higher methane content than cassava peel. A large bucket was used to measure the biogas yield leading to a very low accuracy.

8. Groundnut Husk (GH)

The effects of pre-treatment on groundnut husk were investigated by Osman et al. (2006). The study compared the biogas yields of chopped and powdered samples. The reactor was a 3 L vessel which was stirred by hand twice a day. Gas measurements started after production of combustible gas leading to a loss of valuable data of earlier biogas yields. CO_2 composition was measured using the "Ellegard and Agneus" method. Results showed crude fibre content of cellulose, hemicellulose and lignin of 34.91, 10.3 and 24.27% respectively before digestion and 33, 14 and 6.3% respectively after digestion. This indicated a low digestibility of the crude fibre. The ash content increased from 11.67% to 31%. Biogas production was 8.4 and 18.3 L/kg TS for untreated and physically pre-treated samples. Methane content was 58.30 and 58.6% for untreated and physically pre-treated samples. The conclusion was that physically pre-treated groundnut husk has a higher biogas yield.

9. Ugwu Stalk (US)

A literature search produced no results on the AD of ugwu stalk.

The results of the literature review on local anaerobic digestion studies show that almost all the local tests did not follow any standard experimental method. Reactor vessels were too large for laboratory scale tests, which led to the anaerobic digestion tests being performed under ambient temperatures which varied widely during the tests. In some studies the values ranged from 22-38^{O}C preventing the reproducibility of the test. None of the local studies indicated any purging of the bioreactors to create anaerobic conditions. Methane presence in biogas was confirmed by a flammability test which is unable to analyse the actual methane content. Tests were not replicated to confirm repeatability which also led to an absence of statistical analysis. In some cases there was no mention of the quantity of substrate used for tests in addition to missing or insufficient data about inoculum and chemical additives. Graphs were poor and illegible. Most importantly conclusions were made with no evidence to back them up. The absence of quality data from acceptable experimental methods, creates a gap in knowledge on the biogas yields of various Niger Delta food wastes.

2.4 Renewable Energy, Rural Electrification and Environmental Regulations

This section presents an overview of Nigerian policies and regulations that support the implementation of the findings of this study.

2.4.1 National Energy Policy

The National Energy Policy (NEP, 2003) was created by the Energy Commission of Nigeria in 2003. The document focuses on the optimal utilisation of the nation's energy sources for sustainable development. The policy discusses the multidimensional nature of energy and addresses diverse issues such as research and development, energy pricing and financing, legislation, energy efficiency and environment. Its scope includes renewable energy sources including hydropower, solar, biomass, wind, hydrogen and other renewables. The objectives of the policy cover the development of the nation's energy sources and guaranteeing a stable and sufficient supply of energy in an environmentally friendly manner. Its scope extends to promoting investment in the energy sector and using the nation's energy resources to promote international cooperation.

2.4.2 Electric Power Sector Reform Act

The Electric Power Sector Reform Act (EPSRA, 2005) was enacted by the National Assembly of Nigeria in 2005. The act provides for the licensing and regulation of the generation, transmission, distribution and supply of electricity in the country by establishing the National Electricity Regulatory Commission (NERC), Rural Electrification Agency (REA) and the Rural

Electrification Fund (REF). The NERC ensures the efficient and reliable provision of electrical services in both rural and urban areas. It also controls the issuance of licenses for energy generation and distribution. In relation to licensing, there is an exemption to the regulation when the generated electricity does not exceed 1 megawatt (MW) and distributed electricity is below 100 kilowatts (kW). The Act also establishes the REA that shall deal with the expansion of the main grid, development of isolated and mini-grid system and renewable energy power generation.

2.4.3 Renewable Energy Master Plan

The Renewable Energy Master Plan (REMP, 2012) is a roadmap articulating Nigeria's vision to increase the role of renewable energy in achieving sustainable development. The original master plan was prepared in 2005, but had to be revised in 2012 to take into consideration new policy guidelines, developments at the national/international scene and finally to reduce the voluminous initial master plan into a more concise report. The objectives of the Master Plan are enhancing energy security, expanding access to energy especially rural areas, stemming rural to urban migration, reducing environmental degradation and improving research and development on various renewable energy technologies.

2.4.4 National Renewable Energy and Energy Efficiency Policy

The National Renewable Energy and Energy Efficiency Policy (NREEEP, 2015) was adopted in 2015. The policy sets out a framework for action to address Nigeria's access to modern and clean energy sources and to meet up to improved energy security and climatic objectives. The document addresses diverse issues that include renewable energy, supply and utilisation, regulations, legislations, standards, research and development, environmental issues, pricing and financing. It also addresses the issue of energy conservation with the aim of reducing the amount of energy required to provide goods and services. The renewable energy technologies that the policy addresses are: hydropower, biomass, solar, wind, geothermal, wave and tidal energy plants.

2.4.5 Renewable Electricity Policy Guidelines

The Renewable Electricity Policy Guidelines, (REPG, 2006) are policy guidelines established by the former Ministry of Power and Steel in 2006 to serve as an overarching policy for all electricity derived from renewable energy sources. It also serves as a framework to integrate renewables into the national electricity supply network. The objectives of the guidelines include expanding electricity generating capacity to meet the national demand by increasing access to electricity, encouraging the diversification of sources of electricity and stimulating growth in the renewable electricity sector leading to more jobs and technological development. Others are developing regulatory procedures tailored towards the peculiarities of

renewable electricity supply and reducing household air pollution leading to improved health and social development.

2.4.6 Regulations on Feed in Tariff for Renewable Energy Sourced Electricity in Nigeria

The Regulations on Feed in Tariff for Renewable Energy Sourced Electricity in Nigeria (REFIT-RESEN, 2015) is a set of regulations guiding the distribution and transmission of renewable energy based electricity that is connected to the transmission grid or distribution networks with a capacity above 1 MW. The objectives of the regulation are to boost power supply, enhance the attainment of renewable electricity targets, develop and incorporate viable renewable energy resources into the national energy mix. Others are establishing a guaranteed price for renewable electricity that provides adequate return on investment, providing priority grid access for renewable electricity, creating a purchase obligation for renewable electricity and attracting private sector participation in the sector. The regulation has measures in place to ensure that renewable electricity is purchased by off-takers, who are retailers of electricity, and distributed to grid connected end-users.

2.4.7 Independent Electricity Distribution Networks Regulation

The Independent Electricity Distribution Networks Regulation (IEDNR, 2012) was developed in 2012 by the National Electricity Regulatory Commission based on powers conferred on it by the Electricity Power Sector Reform Act of 2005. The regulations apply to all independent electricity distribution systems, owners, operators and users in Nigeria. These include isolated off-grid rural Independent Electricity Distribution Networks, IEDN, isolated off-grid urban IEDN and embedded IEDN. The objective of the Regulation is to provide standard rules for the issuance of distribution licenses to qualified operators and licensees to engage in electricity distribution, independent of the distribution system operated by the Distribution Company of Nigeria. The regulation mandates the NERC to grant licenses for distribution systems that cover specific geographical areas.

2.4.8 Embedded Generation Regulations

The Embedded Generation Regulations (EGR, 2012) was established in 2012 by the National Electricity Regulatory Commission based on powers conferred on it by the Electricity Power Sector Reform Act of 2005. The regulations apply to embedded generation licensees, prospective embedded generation licensees, applications for embedded licenses and distribution networks. The objective of these Regulations is to provide standard rules for embedded generation and distribution of electricity to ensure safe, secure and efficient electricity supply. The regulations apply to users of Distribution Networks and embedded generator licensees. The regulation also specifies that in the case of renewable energy where storage is not required, operators

of Renewable Energy Power Systems shall ensure that flexible generation shall exist to allow power to be absorbed into the network on a priority basis. It also species that Feed-In-Tariffs (FITs) shall be applied to energy produced from Renewable Energy Embedded Generators.

2.4.9 Nigerian Biofuel Policy and Incentives

The Nigerian Biofuel Policy and Incentives (NBPI, 2007) is a framework developed by the Nigerian National Petroleum Corporation (NNPC) in 2007. It was part of the corporations mandate to create an enabling environment for the establishment of a domestic fuel ethanol industry. The policy strives to reduce the nation's dependence on imported fuels, while reducing environmental pollution and creating jobs. The policy identifies biomass as agriculturally produced raw materials that are available on a renewable or recurring basis, industrial waste and the biodegradable component Municipal Solid Waste. Its description of biofuels is limited to fuel ethanol, bio-diesel and other fuels from biomass primarily used for automotive, thermal and power generation purposes. The objective of the policy is to firmly establish a thriving fuel ethanol industry, utilizing agricultural products as a means of improving the quality of automotive fossil-based fuels in Nigeria.

2.4.10 Rural Electrification Policy Paper

The Rural Electrification Policy Paper (REPP, 2009) was developed in 2009 by the Ministry of Power and expresses the intentions of the Federal Government of Nigeria (FGN) to enable greater access to electricity and to enhance sustainable economic and social development throughout Nigeria. The regulatory framework for the Policy comes from the Electric Power Sector Reform Act (EPSRA) and covers generating schemes above 1MW and distribution schemes above 100kW. The objectives of the policy are to stimulate economic and social activities in rural areas, raise the living standard of rural populations through improved lighting, promote the use of environmentally friendly alternatives to fossil fuels and fuel wood. Others include reducing the urban rural migration and protecting the nations environment by reducing pollution.

2.4.11 National Policy on Environment

The National Policy on Environment (NPE, 1999) is a policy that was published in 1999 by the Ministry of Environment to define a framework for the environmental governance of Nigeria via environmental protection and conservation of natural resources for sustainable development. The policy also seeks to promote good environmental practice through environmental awareness and education. The objectives of the policy include securing a quality environment adequate for good health, promoting sustainable use of natural resources and encouraging individual and community participation in environmental improvement initiatives. Others are engendering a national culture of environmental preservation and building partnerships among all

stakeholders on environmental matters. The policy identifies water, air and soil as the three natural mediums that are mainly affected by environmental degradation. It specifically addresses floods and erosion, sanitation and waste management as the major causes of environmental degradation and mentions strategies to mitigate them.

2.4.12 National Environmental Regulations

The National Environmental Standards and Regulations Enforcement Agency (NESREA, 2013) has developed 24 Environmental Regulations that are currently in full effect. The regulations are to ensure that the fragile environment is not destroyed by the national development agenda of the country. The regulations related to findings of this study are listed below:

Wetlands, River Banks and Lake Shores

Regulations 2009 26 provides for the conservation and sustainable use of wetlands and for ecological and tourism purposes and to protect the flora and fauna species in the wetlands.

Sanitation and Wastes Control

Regulations 2009 28 minimizes pollution by providing the legal framework for sustainable and environmentally friendly practices in sanitation and waste management.

Permitting and Licensing System

Regulations 2009 29 makes sure environmental laws, regulations and standards are fully applied.

Coastal and Marine Area Protection

Regulations 2010 18 provides the regulatory framework to prevent the degradation of the coastal and marine environment.

Surface and Groundwater Quality Control

Regulations 2010 22 is to remediate the polluted nation's surface water and to protect existing surface waters uses.

2.5 Chapter Summary

The chapter presents an overview of the anaerobic digestion process. Anaerobic digestion is the degradation of complex organic compounds for the production of biogas. The process consists of four stages namely: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Some feedstock used for the process consists of complicated molecules that need to be broken down into simpler forms so that they can be accessible to the microbes. This action of simplifying the feedstock is known as pre-treatment and falls into physical, chemical, biological or combined pre-treatment methods. Some substances also inhibit the efficient production of biogas

during digestion. These include: ammonia, sulphides and heavy metals, which affect the microbe's ability to digest the nutrients. Additionally the biogas might need to be cleaned of impurities for certain uses such as injection into the national gas grid, fuel for gas turbines and biogas vehicles. The AD process utilises a closed carbon cycle to reduce greenhouse gas emissions. A mixture of feedstock that have complementary characteristics can be co-digested to produce more biogas than if they were individually digested.

Various models exist for determining the biogas potential of feedstock. Buswell, Boyle and Baserga Equations utilise the chemical or nutrient compositions of substrates to predict biogas production. Monod, Contois, Chen and Hashimoto Models and the Modified Gompertz Equation utilise growth rate kinetics to predict biogas potential. The IWA Anaerobic Digestion Model 1 is a comprehensive model that uses numerous input parameters to produce multiple stoichiometric and kinetic equations.

Water Hyacinth is an aquatic weed that thrives in fresh waters of tropical climates. The plant causes numerous socio-economic problems including: flooding, blockage of irrigation and hydropower systems, water transport disruption, home to dangerous wild animals and disease carrying vectors, destruction of biodiversity and increase in evapotranspiration. Despite its negative effects, the Water Hyacinth is a storehouse of energy that can be used as feedstock for the AD process. The plant consists of complex compounds of cellulose, hemicellulose and lignin and needs to be pre-treated before its gas production potential can be attained.

The Niger Delta is an oil rich region in the southernmost coast of Nigeria that has experienced extensive environmental degradation from oil processing, water hyacinth infestation, burning of traditional biomass and deforestation. The most commonly consumed foods in the region are yam, cassava, cocoyam, plantain, corn, egusi, beans, groundnut and ugwu. These foods produce the following waste: yam, cassava, cocoyam and plantain peels, corn cob and husk, egusi shell, bean skin, groundnut husk and ugwu stalk. A literature review of the characterisation of these food wastes showed limited studies with none on egusi shell and ugwu stalks. A review of the studies on the anaerobic digestion of the same wastes showed that almost all the tests did not follow any standard experimental method. Reactor vessels were too large for laboratory scale tests, processes were run at ambient temperatures which varied widely during the tests, bioreactors were not purged of oxygen, and actual methane contents were not measured. Furthermore tests were not replicated to confirm repeatability, which also led to an absence of statistical analysis. There was also insufficient information on the quantity and type of substrates, inoculum and chemical additives with conclusions being made without any evidence to back them up.

There are various Nigerian regulations and policies which support the adoption, implementation and deployment of technologies related to this study. Most important is the exemption of generating capacities below 1MW from regulations. This limit is higher than the low power demand of remote communities. This allows for communities and individuals to easily adopt such renewable technologies and avoiding the bureaucratic bottle necks of getting various approvals from the government. Many of the policies also provide financial incentives that would encourage investors to participate in the renewable energy sector.

The second chapter covered an overview of the Anaerobic Digestion process including the models utilised in the study of biogas production. The aquatic plant water hyacinth water introduced with its role as an AD feedstock was presented. A brief background of the Niger Delta is presented including the most commonly consumed foods and their waste products. The chapter closed with an overview of the local policies and regulations governing renewable energy and environmental management. The next chapter presents the experimental methods used to obtain the results of this research study.

Chapter 3 Experimental Methods

The previous chapter presented an overview of the AD process, water hyacinth digestion, common Niger Delta food waste and local renewable energy policies. This chapter describes the experimental methods that were used for the AD testing of the food wastes and water hyacinth. The methods included those for measuring the waste content of each food item, characterising the food waste and quantifying the annual production of wastes. This was followed by the methods used for designing and building various configurations of bioreactors. The chapter closed with the description of the Bio-Methane Potential tests and the statistical analyses performed on the results.

3.1 Food Waste Content

This section describes the method for quantifying the waste produced from each food type. The results were used to calculate the Specific Waste Index of the various foods. The Specific Waste Index is the ratio of waste produced to the consumable product (Russ and Meyer-Pittroff, 2004). The equation is shown in (8). The accumulated waste (food waste content) and consumable product were determined experimentally by weighing the samples.

$$SWI = Mass_{accumulated\ waste}/Mass_{consumable\ Product} \quad (8)$$

Procedure

- 500 kg of each of the nine food samples were obtained from the Ridley Road Food Market, London.
- The samples were taken to the laboratory and rinsed with water to remove extraneous particles and dried in a fume hood for 30 minutes.
- The food samples were weighed.
- The wastes from the foods were extracted using methods describes in the next section.
- The wastes from the foods were weighed.
- The weights of the food items were then divided by the weights of their respective waste products to determine the SWI of each food item.

The weight of the foods and wastes were measured using the Adam Equipment PGL 2002 Precision Balance shown in Figure 3-1. The scale has a maximum capacity of 2000 g and readability of 0.01 g. The tests were performed in triplicates to improve precision. The pictures of the food wastes from the nine samples are presented in Figure 3-2 and their methods of extraction are described below.

Figure 3–1 Adam Equipment PGL 2002 Precision Balance used in measuring the mass of food items and their waste products

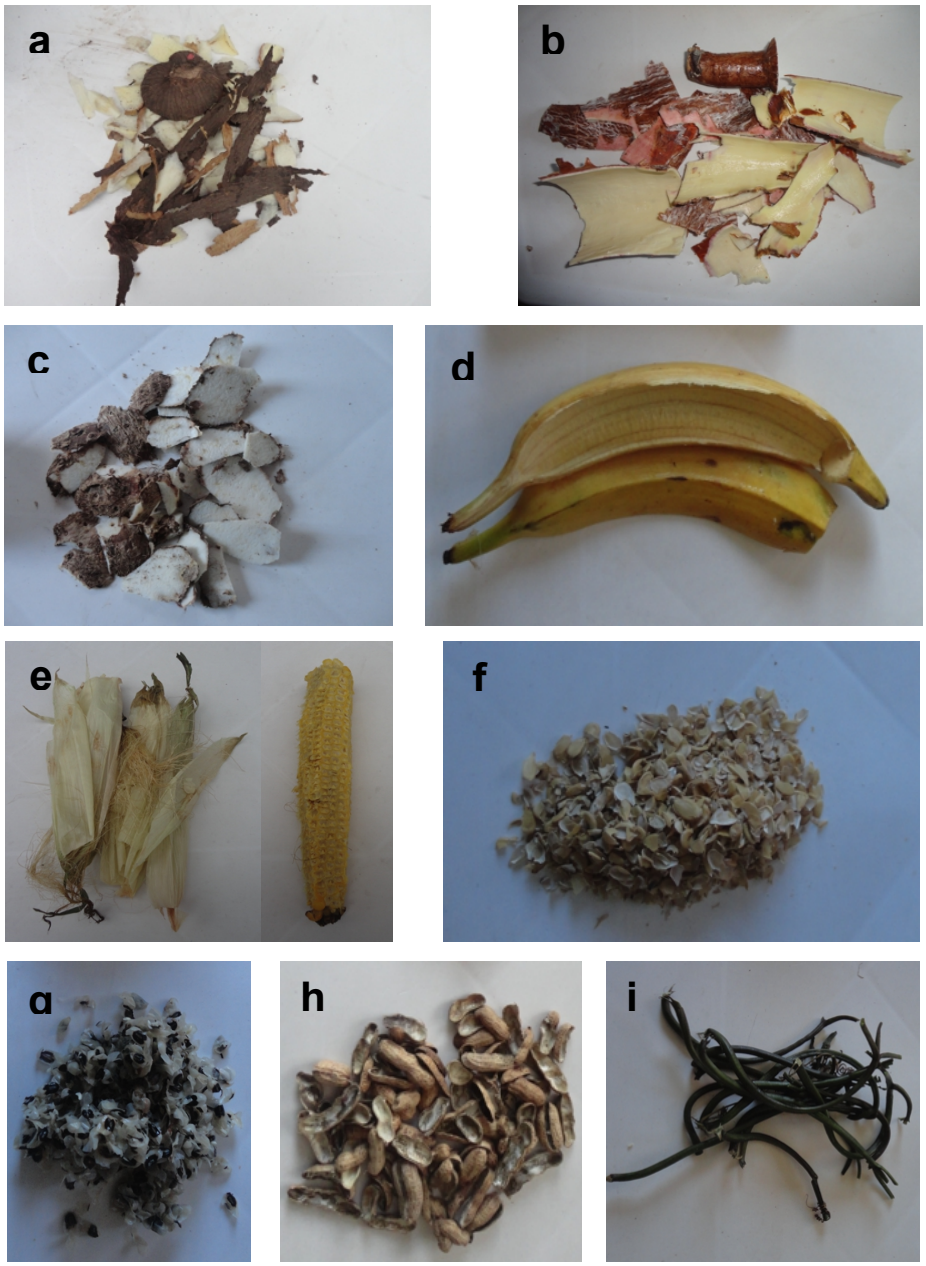


Figure 3–2 Unavoidable Food Waste from nine Niger Delta foods (a) Yam Peel (b) Cassava Peel (c) Cocoyam Peel (d) Plantain Peel (e) Corn Cob and Husk (f) Egusi Shell (g) Bean Skin (h) Groundnut Husk (i) Ugwu Stalk

The wastes from the tubers, which consist of yam, cassava and cocoyam, are known as yam, cassava and cocoyam peel respectively. They are obtained by using a kitchen knife to cut off thin slices of their outer coats. The plantain's waste is known as plantain peel and is derived by inserting a knife into the top of the plantain and making a cut to the bottom. The outer coat is then peeled off. Corn has two waste products, the husk and cob. The husk is peeled off the corn ear while the cob is obtained after the ear has been boiled and the kernels extracted.

Egusi seeds produce a waste called egusi shell, which is collected by breaking off the outer coat of the seed with fingers. The waste from the beans is known as bean skin and is recovered after soaking the beans in water for four hours. The beans are then rubbed together and the softened skin easily comes off. Groundnut produces groundnut husk, which is extracted by cracking the nut with fingers. The waste of ugwu is the ugwu stalk and is separated from the plant after stripping off the leaves.

For the yam, cassava, cocoyam, plantain, corn and ugwu samples, they were individually weighed on a cleaned precision balance. Their wastes were then extracted and weighed on the balance. The rest of the samples of egusi, beans and groundnut were too small to be individually weighed on the scale. Hence these samples were weighed in approximately 100 g groups. The group wastes were then extracted and weighed as well. The tests were performed in triplicates and the results were used to calculate the SWI values for each sample.

3.2 Food Waste Characterisation and Bio-Methane Potential of Food Waste

This section describes the methods used to characterise the food waste and determine their theoretical bio-methane potential.

3.2.1 Food Waste Characterisation

The characterisation of each food waste was determined using standard methods. Due to the requirement for analytical chemistry procedures, the food waste samples were sent to NRM Laboratories, Bracknell, UK for the waste characterization.

Procedure

- 500 g of each food waste sample was weighed.
- The samples were placed in a clean laboratory sample bag and transported to the NRM laboratories for waste characterisation.
- The samples were analysed using standard proximate analysis methods described in the next section.
- The results of the analysis were sent back for recording.

Total Solids (TS)
Total solid is the dry matter of a sample after the moisture has been completely removed. To measure the total solids, the sample is initially weighed. Next the sample is dried in an oven to a constant weight at $105^{O}C$. The residue is then weighed and the result is the total solid content of the sample.

Volatile Solids (VS)
Volatile Solid is the organic dry matter of a sample. To measure the VS, the sample is dried to constant weight in an oven. After drying, the sample is weighed then placed in a furnace and ignited at $550^{O}C$ for four hours. The residue is then taken out of the furnace and weighed. The difference in weight between the initial mass and the residue is the volatile solid content.

Crude Fibre (CrF)
Crude Fibre is the indigestible carbohydrate of a sample. It consists of true cellulose and insoluble lignin. Crude fibre is loss on ignition of dried residue remaining after digestion of sample with 1.25% H_2SO_4 and 1.25% NaOH solutions under specific conditions. The sample is placed in a flask and the H_2SO_4 solution is added. The contents are then boiled for 30 minutes and then left to rest for one minute. The contents are then filtered and the residue is transferred to a flask with a boiling NaOH solution for 30 minutes and left to rest for one minute. The residue is then washed, dried and weighed.

Crude Protein (CrP)
Crude Protein is the amount of protein found in a sample as determined by its Nitrogen content. It is analysed using Kjeldahl's method which evaluates the total nitrogen content of the sample after it has been digested in sulphuric acid with a mercury or selenium catalyst.

Crude Fat (OAH)
Crude fat is the mixture of fat-soluble materials present in the sample. It can also refer to the free lipid content. The analysis method involves the fats being extracted from the sample with petroleum ether and evaluated as a percentage of the weight before the solvent is evaporated.

Nitrogen Free Extract (NFE)
Nitrogen Free Extracts are the non-Nitrogen soluble organic compounds including carbohydrates, such as starch and sugar. The value is calculated by subtracting the sum of the Crude Fibre, Crude Protein, Crude Oil and Ash from the Total Solids content.

Ash

The Ash is the total mineral matter of a sample. To measure the value, a sample is dried to constant weight in an oven. After drying, the sample is weighed then placed in a furnace and ignited at 550^{O}C for four hours. The residue is then taken out of the furnace and weighed and the result indicates the ash content of the sample.

Moisture Content

The moisture content is the liquid component of a sample. To measure the moisture content, the sample is initially weighed. Next the sample is dried in an oven to a constant weight at 105^{O}C. The residue is then weighed and its weight is subtracted from the initial weight of the sample. The final result, which indicates the loss in weight, is the moisture content of the sample.

3.2.2 Bio-Methane Potential of Food Waste

The theoretical Bio-Methane Potentials of the feedstock were calculated using the Baserga Model (Baserga, 1998). The model is used to determine the theoretical bio-methane potential of a substrate based on its nutrient composition. The input data required for the use of the model are the Crude Fiber *(C_rF)*, Crude Protein *(C_rP)*, Crude Oils *(OAH)*, Nitrogen Free Extracts *(NFE),* Ash and Moisture content of the samples. The model assumes that all the organic content in the sample is converted to biogas. The full set of constants and equations for the model are presented below:

Digestibility Factors:

Crude Fibre	*(C_rFd)*	*74.3%*
Crude Protein	*(C_rPd)*	*65.09%*
Crude Fat	*(OAHd)*	*67.51%*
NFE	*(NFEd)*	*69.97%*

Gas Yield Conversion Factors:

Carbohydrates	*(GYCf)*	*790 l/kg*
Proteins	*(GYPf)*	*700 l/kg*
Fat	*(GYOf)*	*1250 l/kg*

Methane content of Biogas:

Carbohydrates	*(MCf)*	*50%*
Proteins	*(MPf)*	*71%*
Fats	*(Mof)*	*68%*

Calculated Parameters

$NFE = 100 - (C_rP + C_rF + OAH + Ash + Moisture)$

$VS = (C_rF + C_rP + OAH + NFE)$

Baserga Equations:

$Digestible\ Carbohydrate\ \left(\frac{g}{kg}DMB\right)\ DC = ((C_rF \times C_rFd) + (NFE \times NFEd))/10$

$Digestible\ Crude\ Protein\ \left(\frac{g}{kg}DMB\right)\ DP = (C_rP \times C_rd)/10$

$Digestible\ Crude\ Fat\ \left(\frac{g}{kg}DMB\right)\ DO = (OAH \times OAHd)/10$

And :

$Digestible\ Carbohydrate\ \left(\frac{kg}{kg}VS\right) DCv = DC/(VS \times 10)$

$Digestible\ Crude\ Protein\ \left(\frac{kg}{kg}VS\right) DPv = DP/(VS \times 10)$

$Digestible\ Crude\ Fat\ \left(\frac{kg}{kg}VS\right) DOv = DO/(VS \times 10)$

And :

$Gas\ Yield\ Carbohydrate\ \left(\frac{l}{kg}VS\right)\ GYC = DCv \times GYCf$

$Gas\ Yield\ Proteins\ \left(\frac{l}{kg}VS\right)\ GYP = DPv \times GYPf$

$Gas\ Yield\ Fat\ \left(\frac{l}{kg}VS\right)\ GYO = DOv \times GYOf$

$\boldsymbol{Total\ Gas\ Yield}\ \left(\frac{\boldsymbol{l}}{\boldsymbol{kg}}\boldsymbol{VS}\right)\ \boldsymbol{TGY = GYC + GYP + GYO}$

And :

$Methane\ Share\ for\ Carbohydrates\ (\%)\ MC = GYC \times MCf/TGY$

$Methane\ Share\ for\ Protein\ (\%)\ MP = GYP \times MPf/TGY$

$Methane\ Share\ for\ Fats\ (\%)\ MO = GYO \times MOf/TGY$

$\boldsymbol{Total\ Methane\ Content}\ (\%)\ \boldsymbol{TMC = MC + MP + MO}$

And :

$$\boldsymbol{Gas\ Yield}\ (\frac{\boldsymbol{m^3}}{\boldsymbol{tonne}})\boldsymbol{of\ Fresh\ Matter} = (\boldsymbol{TGY}\times\boldsymbol{VS})/\boldsymbol{100}$$

3.3 Food Waste Quantification and Bioenergy Potential of the Niger Delta

This section describes a method for estimating the regional waste production and bioenergy potential from the common Niger Delta foods. The annual waste production of each food by an individual was calculated using the frequency of consumption of the food and its waste content. The regional amount of waste was calculated using the 2020 projected population of the region. The results were used to determine the regional biogas yield and clean energy potential of the Niger Delta.

Assumptions in line with (Ene-Obong et al., 2013):

- Each individual eats 0.2 kg of each food item per day.
- Each individual eats the food item once a day.
- Men, women and children eat the same amount of food.
- Each food is prepared using the same method.

The complete set of equations for the regional waste production and bioenergy potential from the food waste in the Niger Delta is presented below:

Annual Consumption per individual (kg) = daily consumption (kg) × Weekly consumption freq. (week^{-1}) × 52 (weeks)

Annual consumption of population (kg/yr) = Annual consumption per individual (kg) × Population

Annual Food Waste (kg/yr) = Annual Consumption of Pop. (kg) × Waste Content of food (%)

Annual Biogas (m^3/yr) = Annual Food Waste (tonnes) × Total Gas Yield of waste (m^3/tonne)

Annual Methane (m^3/yr) = Annual Biogas (m^3) × Methane Content (%)

Annual Energy (MJ/yr) = Annual Methane (m^3) × Gross Calorific Value Methane (MJ/m^3)

Annual Elect. Energy (kWh/yr) = Annual Energy (MJ) × 0.2778 kWh/MJ

Constants

Gross Calorific Value Methane = 38 MJ/m^3

1 MJ = 0.2778 kWh

3.4 Bioreactor Configuration Tests

This section describes the various configurations of bioreactors that were built and their components.

3.4.1 Configuration 1

Batch Laboratory Anaerobic Digester

This section describes the building and operation of the first configuration bioreactor.

Procedure

- A 500 ml inverted graduated cylinder was filled with water and mounted on a retort stand over a trough of water.
- The heating blanket was connected to the PID temperature controller.
- The pH meter was calibrated using standard solutions.
- Reactor vessel, lid and stirring rod were cleaned using iso-propanol and then rinsed with water and dried.
- A tube was connected from the first port of the reactor lid to the graduated cylinder to measure gas production.
- A pH probe was inserted into the second port of the lid.
- A stopcock was connected via a tube to the third port for injection of inoculum.
- A tube from the Nitrogen cylinder was connected to the fourth port.
- The food sample was weighed and placed in the vessel.
- The stirring rod was placed in the vessel and the reactor was sealed with the lid.
- The magnetic stirrer was switched on at 350 rpm.
- The system was then flushed with Nitrogen.
- The heating blanket was wrapped around the reactor and heated to $37^{O}C$.
- The inoculum was injected into the reactor.
- Biogas production readings were recorded from the water displaced in the graduation cylinder while the pH readings were read from the pH meter digital display.

The picture of the complete reactor is presented in Figure 3-3 while the individual components are presented in Figure 3-4 with their various descriptions.

1. Bioreactor Components

The various components of the Configuration 1 bioreactor system are presented in Figure 3-4.

Reactor Vessel

The reactor vessel is a Duran GL 80 bottle with a polypropylene screw cap consisting of four ports.

- Max operating temperature $500^{O}C$

- Max thermal shock resistance ΔT=100K
- Max temperature of Screw cap 140^{O}C
- Capacity 500ml

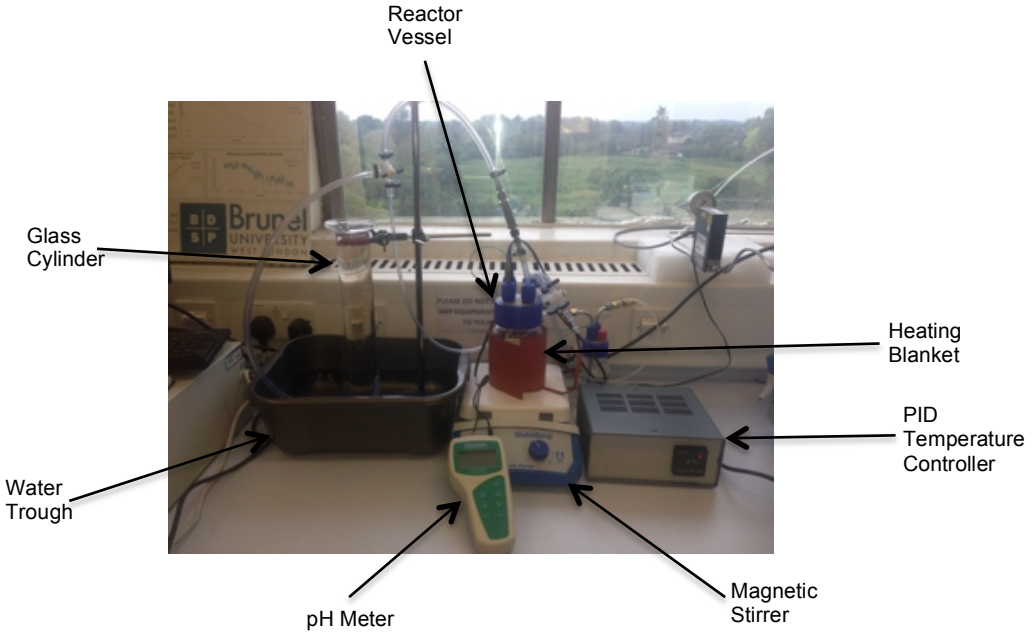


Figure 3–3 Bioreactor Configuration 1 showing the complete digester with reactor, stirrer, heating system and gas collection apparatus

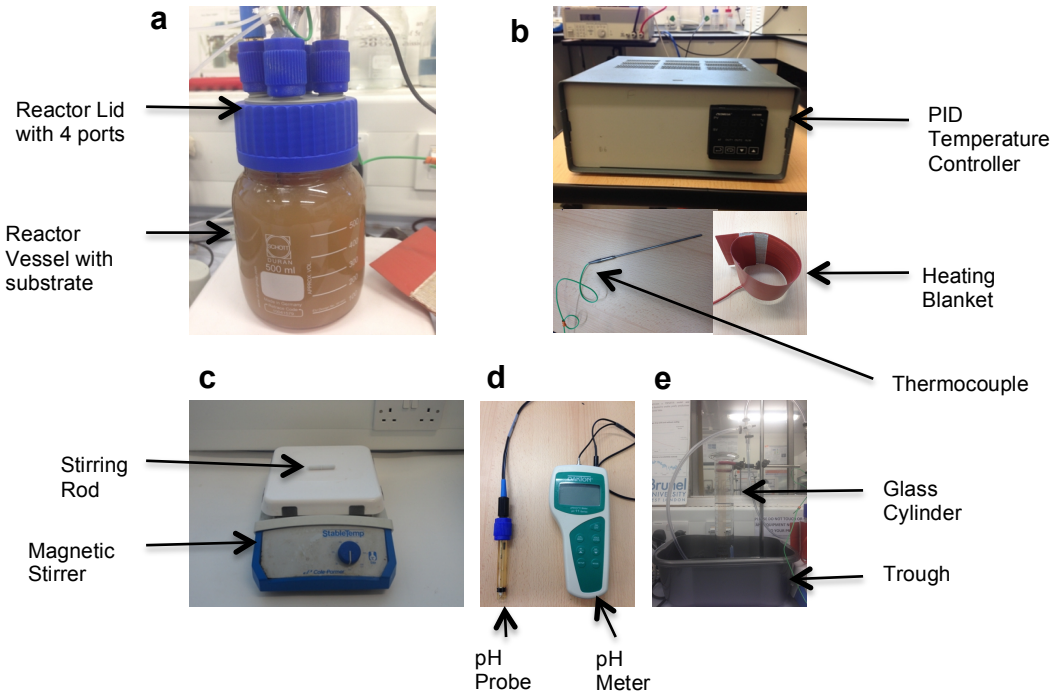


Figure 3–4 Bioreactor Configuration 1 Components. (a) Reactor Vessel (b) Heating System (c) Agitator (d) pH Meter (e) Gas Measurement System

Heating System

The heating system consisted of an Omega CN7833 Temperature and Process PID Controller, an Omega K-type Thermocouple and an Omega SBRH Beaker Heater with the following specifications:

Omega CN7833 Temperature and Process PID Controller

- Resolution 0.1 for thermocouples
- Power consumption 5VA max
- Operating Temperature 0-50^{O}C

Omega K-type Thermocouple

- Temperature range -30 to 350^{O}C

Omega SBRH-series Beaker Heater

- Max Exposure Temperature 232^{O}C
- Power Density 0.008 watts/mm^{2}
- Total Power 250 watts

Agitator

Mixing was achieved via a Coleparmer StableTemp Ceramic magnetic stirrer with the following specification:

- Max speed 1200rpm
- Max stirring volume 4 litres

pH Meter

The pH meter used was an Oakton pH 11 meter with the following specifications:

- pH range 0.00 to 14.00
- pH Accuracy ±0.01
- pH Calibration 5 point manual calibration
- Temperature range -10 to 110^{O}C
- Temperature accuracy ±0.5^{O}C

Gas Measurement System

Gas production was measured using an inverted cylinder over a water basin.

2. Operational Parameters

- The experiment was conducted in batch configuration.
- The digester was a wet anaerobic digestion with a low solid content.
- The experiment was mesophilic at 37^{O}C.
- The pH of the reactants was not externally influenced.
- Retention time was 21 days or less if gas production stopped.
- The system was agitated by magnetic stirrers.
- Heating was externally provided.
- S:I ratio was based on mass.

3.4.2 Configuration 2

Batch Laboratory Anaerobic Digester with data logging capabilities

This section describes the building and operation of the second configuration bioreactor.

Procedure

- The mass flow meter and pressure gauge were mounted on a retort stand.
- A tube was connected from the first port of the reactor lid to the inlet of the flow meter.
- The outlet of the flow meter was connected to the gas analyser.
- Another tube was connected to the second port to serve as an outlet for the Nitrogen gas used for flushing the system.
- The pH meter was calibrated using standard solutions and the pH probe was inserted into the third port of the lid.
- A rubber stopper served as a block for the fourth port.
- The Nitrogen cylinder was connected to the fifth port.
- The pressure gauge was connected to the sixth port.
- The thermocouple was inserted into the seventh port.
- The heating tape was connected to the PID temperature controller.
- Reactor vessel, lid and stirring rod were cleaned using iso-propanol and then rinsed with water and dried.
- The food sample and inoculum were weighed and placed in the vessel.
- The stirring rod was placed in the vessel and the reactor was sealed with the lid and clamp.
- The magnetic stirrer was switched on at 350 rpm.
- The system was then flushed with Nitrogen.
- The heating tape was wrapped around the reactor and heated to $37^{O}C$.
- At $37^{O}C$ the data loggers were all switched on, recording biogas production, pH values, methane and carbon dioxide content.

The picture of the complete system is presented in Figure 3-5 while the various components are presented in Figure 3-6 with their individual descriptions.

1. Bioreactor Components

The various components of the system are presented in Figure 3-6.

Reactor Vessel

The reactor was a custom-made vessel by AM Glassware Scotland who specialise in manufacturing scientific glassware. The reactor consisted of a flanged glass vessel with a PTFE 8-port lid, which was secured to the vessel by a stainless steel quick release clamp. In between the lid and vessel was an FEP coated O-ring to prevent gas leaks.

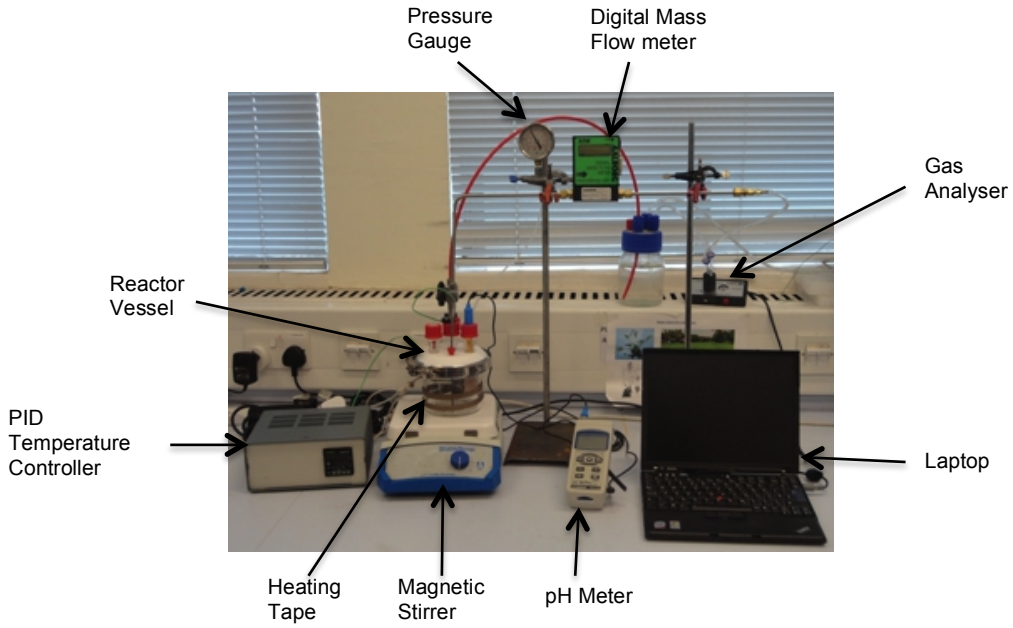


Figure 3–5 Bioreactor Configuration 2 showing the complete digester with reactor, stirrer, heating system, gas flow meter and data logging laptop

Heating System

Heating was provided by the same PID Controller and thermocouple used in Configuration 1. The heating element was an Omega FGSO51 High Temperature Heating Tape which has the following specification:

Omega High Temperature Heating Tape

- Heating element — 36-40 gauge resistance wire
- Di-electric strength — Excess of 2000V
- Maximum exposure temperature — 482^{O}C
- Power Density — 0.013 watts/mm^{2}

Agitator

The mixing system was the same one used in the Configuration 1 system.

pH Meter

The pH meter was an Omega PHH-SD1 data-logging pH meter with the following specification:

- 0.00-14.00 pH measurement
- Real time data logger with auto sampling time 1s to 8h59m59s

- Meter operating temperature 0-50^{O}C
- Electrode operating temperature 0-100^{O}C
- 3 point manual calibration

Gas Measurement System

Gas production was measured by an Aalborg digital mass flow meter with the following specification:

- Gas temp range 0 to 50^{O}C
- Operating temp range -10 to 50^{O}C
- Max gas pressure 500 psig
- Flow accuracy ±1% of FS at calibration temperature and pressure
- Calibration 10 point NIST calibration at 14.7psia and 21.1^{O}C
- Calibration gas 60% CH_4 and 40% CO_2
- Mass Flow 5 ml/min of biogas

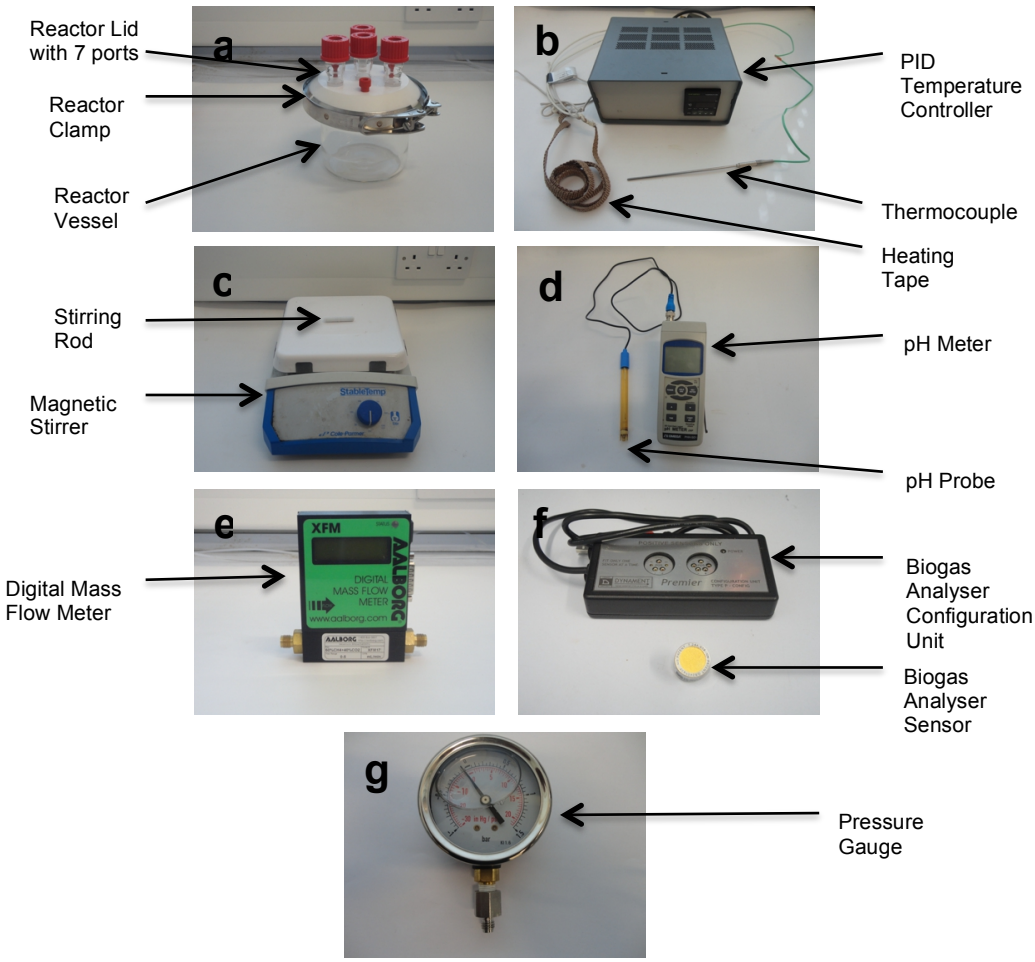


Figure 3–6 Bioreactor Configuration 2 components (a) Reactor Vessel (b) Heating System (c) Agitator (d) pH Meter (e) Gas Measurement System (f) Gas Analyser (g) Pressure Gauge

Gas Analyser

Biogas analysis was performed by an inline Dynament Dual Gas Methane/Carbon dioxide sensor with the following specifications:

- Methane measurement range 0-100% vol.
- Methane resolution (0-10% vol) 0.01%
- Methane resolution (10-100% vol) 0.1%
- Carbon dioxide measurement range 0-100% vol.
- Carbon dioxide resolution (0-100% vol) 0.01%
- Propane measurement range 0-4% vol.
- Propane resolution (0-4% vol) 0.01%
- Operating temperature range -20 to 50^{O}C
- Max operating pressure 1.1 bar

The calibration report for the sensor is presented in Appendix 8.

Pressure Gauge

A generic pressure gauge with a measurement range of -1 to 1.5 bars was used to measure the pressure in the reactor.

2. Operational Parameters

- The experiment took place in a batch digestion system.
- The digestion was wet with a low solid content.
- The experiment was mesophilic at 37^{O}C.
- The pH was not externally influenced.
- Retention time was 21 days or less if gas production stopped.
- The system was agitated by a magnetic stirrer.
- Heating was externally provided.
- S:I ratio was based on mass.

3.4.3 Configuration 3

Multiple Batch Anaerobic Digester

This section describes the building and operation of the third configuration of bioreactor.

Procedure

- Nine inverted cylinders were filled with water and mounted on a custom-made cylinder holder over two troughs of water.
- The heating water bath was switched on and heated to 37^{O}C.
- The pH meter on the reactor lids were calibrated using standard solutions.
- Tubes were connected from the reactor lids to the inlet of the gas sensors.
- Tubes were connected from the outlet of the gas sensors to the graduated cylinders.

- The second ports of the reactor lids were connected to the Nitrogen gas source.
- Reactor vessels and lids were cleaned using iso-propanol and then rinsed with water and dried.
- The food samples and inoculum were placed in the vessel.
- The system was sealed and then flushed with Nitrogen gas.
- The reactors were then placed in the water bath, which was then set to shake at 100 strokes per minute.
- Biogas production was recorded from the water displaced in the graduated cylinder while pH readings were recorded from the digital display of the pH meter. The methane and carbon dioxide content were automatically logged on the laptop.

The picture of the system is presented in Figure 3-7 while the various components are presented in Figure 3-8 with their individual descriptions.

1. Bioreactor Components

The picture of the components of the system are presented in Figure 3-8.

Reactor Vessel

The reactor vessels used were Simax Bottles with pouring ring and GL45 screw caps.

- Max temperature of bottle $500^{O}C$
- Max temperature of screw cap $140^{O}C$
- Capacity 500 ml

Heating System and Agitator

The heating and mixing system were both combined in a Grant Instruments SS40D Shaking Water Bath with the following specifications:

- Temperature range $0\text{-}100^{O}C$
- Shaking speed 20-220 strokes/min

pH Meter

The pH meter was a Hanna HI98103 pH tester with the following specification:

- pH range 0.00 to 14.00
- Accuracy ±0.2
- Calibration Manual 2 points
- Operating temperature $0\text{ -}50^{O}C$

Gas Measurement System

Gas production was measured by inverted graduated cylinders immersed in a basin of water.

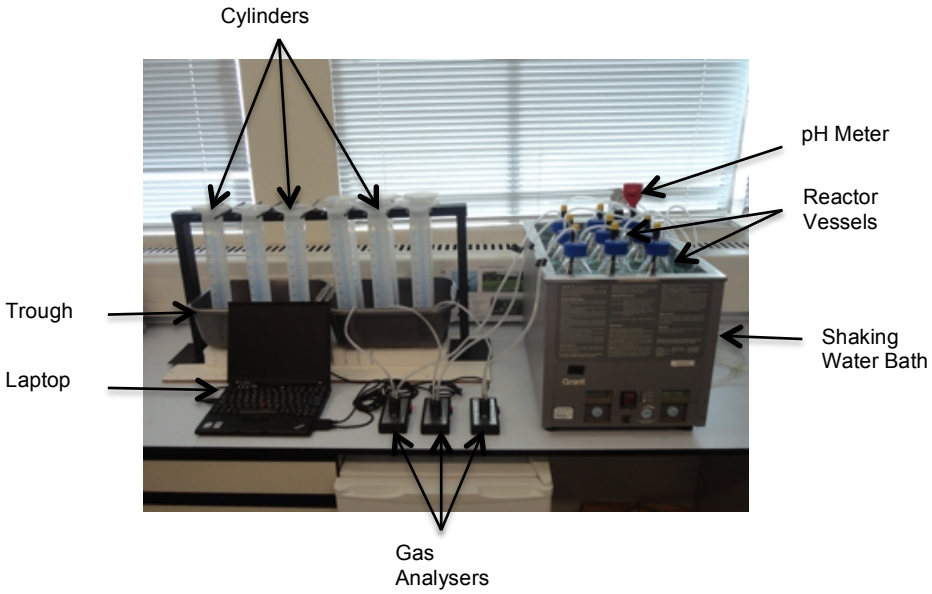


Figure 3–7 Bio-reactor Configuration 3 showing the multi vessel reactor which includes shaking water bath, gas collection system and data logging laptop

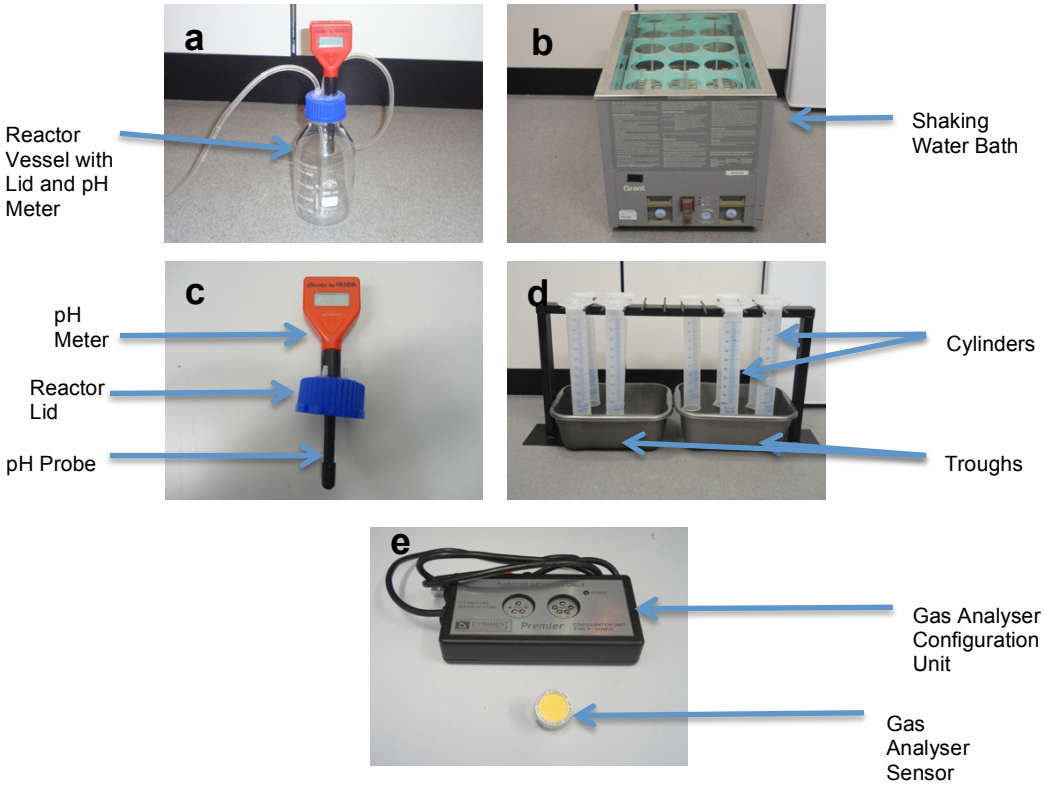


Figure 3–8 Bioreactor Configuration 3 components (a) Reactor Vessel (b) Heating System and Agitator (c) pH Meter (d) Gas Measurement System (e) Gas Analyser

Gas Analyser

Biogas analyser was the same one used in Configuration 2. The calibration report for the sensor is presented in Appendix 8.

2. Operational Parameters

- The experiment was conducted under batch conditions.
- The digester was a wet anaerobic digestion with low solid content.
- The experiment was mesophilic at a 37^{O}C.
- The pH of the reactants was not externally influenced.
- Retention time was 20 days.
- The test took place in a shaking water bath at 100 strokes per minute.
- Ratio of S:I was 1:2 on a VS basis.
- Ratio of Food Waste to WH was 2:1 on a VS basis.

3.5 Bio-Methane Potential Experiments

This section describes the experimental methods used to perform the bio-methane potential tests on water hyacinth with yam, cassava, cocoyam and plantain peels. The VDI 4630 (VDI, 2006) was selected as the BMP experimental method for this study due to it wide use in literature for co-digestion tests. Furthermore Pham et al. (2012) compared the VDI 4630 to other widely used BMP test methods. The results showed that it reached steady conditions in a shorter period, reducing digestion time

3.5.1 Inoculum

This section describes the collection and pre-treatment of the inoculum that was used for the AD experiment.

Procedure

- Inoculum was obtained from Anaerobic Digestion plant at Camley Street Natural Park, London shown in Figure 3-9.
- The inoculum was filtered through a sieve in order to remove coarse particulates.
- The inoculum was then analysed for TS and VS content.
- 500 g of inoculum was measured into nine 500 ml vessels and placed into the Third Configuration Bioreactor.
- The inoculum was pre-treated in the bioreactor for a week in order to de-gas the inoculum and create a hunger phase for the microbes.

In more detail, the Camley digester is 2 m^3 in size and has been running for over 2 years. The digester is fed catering food wastes from local canteens and offices. The wastes consist of fruit and vegetable peels, eggshells, coffee grounds, chips and bacon. The feedstock is macerated in a separate tank and 2 kg of it is automatically fed into the digester every two hours by an electric pump. A chemical analysis of the digestate, performed by the operator is presented in Appendix 6. The nutrient characterisation of the inoculum performed by this study is presented in Appendix 7.

Figure 3–9 Camley Anaerobic Digester system showing macerator, bio-digester, digestate tank and biogas holder.

The inoculum was prepared in line with VDI 4630 guidelines. After collection, the inoculum was filtered through a sieve in order to remove coarse particulates and increase the Volatile Solid to Total Solid ratio. The inoculum had a Total Solid content of 5.4% and a Volatile Solid of 3.4% or 62% VS/TS. This aligns with the VDI 4630 requirement of the inoculum having at least 50% VS/TS.

The reactor vessels used for the tests were 500 ml and would hold 500 g (16.8 g VS) of inoculum. In order to prevent inhibition by accumulation of organic acids, the ratio of the substrate to inoculum should be at least 1:2 (VDI, 2006). For this experiment, the S:I ratio to be used is 1:2 on a VS basis. This value was also selected because higher S:I ratios lead to a decrease in the amount of biogas produced (Kafle et al., 2014; Cheng and Zhong, 2014; Seno et al., 2010; Feng et al., 2013; Gonzalez-Fernandez, 2009; Liu et al., 2009). Using the S:I of 1:2, the amount of substrate for each batch can be calculated from the corresponding inoculum mass of 16.8 g VS using:

$$S:I = 1:2 = 8.4 : 16.8 \text{ (g VS)}$$

The substrate in each digester batch will be 8.4 g VS. In the case of mono-digestion 8.4 g VS will be the total mass of the food waste while in the case of co-digestion 8.4 g VS will be the combined mass of both the Food Waste and Water Hyacinth in the specified ratio of 1:2.

The inoculum was pre-treated using the third configuration bioreactor. The shaking water bath was filled with water and heated to 37^{O}C. Nine 500 ml reactor vessels were then placed into the bath. 500 g of the inoculum was weighed on a scale and poured into each of the nine reactor vessels and sealed with the lid. The reactors were connected, via tubing, to the gas measurement system to facilitate the release of the inoculum's residual

biogas. The basin water also prevented atmospheric oxygen from infiltrating the vessels. The vessels were then flushed with Nitrogen to create anaerobic conditions. The setup was allowed to run for a week in order to fully de-gas the inoculum and allow the microbes adapt to the new environment. This process also created a “hunger phase” which meant the microbes were starving for nutrients and would rapidly consume the introduced substrates.

3.5.2 Food Waste

This section describes the procedure of obtaining and pre-treating the food waste samples.

Procedure

- One kg of each food sample was obtained from the Ridley Road Market.
- The samples were rinsed to remove extraneous particles and then dried in a fume hood.
- Wastes were extracted from the samples using local food processing methods specific to each food item.
- 100 g of waste samples were dried at $80^{O}C$ until constant weight was obtained.
- The dried samples were ground into a fine power using a high-speed mill with a grinding speed of 19,000 rpm.
- The milled samples were sifted through a 0.5 mm sieve.
- The processed samples were weighed and 8.4 g VS of each was kept for mono-digestion tests while 5.6 g VS of each was kept aside for co-digestion tests. Excess samples were stored in airtight containers.

In more detail, one kilogram each of Yam, Cassava, Cocoyam and Plantain were each purchased from the Ridley Road Market, London. The wastes from the samples were obtained using the waste extraction process described in Section 3.1. The peels were transported to the laboratory and decontaminated by rinsing with deionized water to remove dust, coarse particles and other extraneous contaminants. After rinsing, the samples were dried in a fume hood to remove residual moisture from the surface of the peels. A sample of each substrate was tested to determine its Total Solid and Volatile Solid content and the results are presented in Table 3-1.

Table 3–1 Total and Volatile Solid content of substrates

Food Waste	VS (%)	TS (%)	VS/TS (%)
YP	23.3	25.2	92.5
CP	32.2	34.2	94.1
CoP	15.8	17.3	91.5
PP	12.9	14.2	90.8

The peels were then cut into 2 cm pieces and then heat dried in a Thermo Scientific Lindberg Blue M box furnace shown in Figure 3-10 at 80^{O}C for 24 hours in order to stabilize the tissue and stop enzymatic reactions (Campbell and Plank, 1997).

Figure 3–10 Thermo Scientific box furnace used for drying of food waste samples

The samples were dried at 80^{O}C because below this value all moisture may not be removed and above it, thermal decomposition may reduce the dry weight of the sample. After drying, the various food wastes were individually ground in a Waring WSG30 high-speed super fine grinder shown in Figure 3-11 with a grinding speed of 19,000 rpm.

The wastes were ground into fine powder and sieved through a mesh of 0.5 mm. The milling reduced the particle size of the substrates leading to an increase in surface area for bioactivity. This leads to an increase in biogas productivity and reduction of technical digestion time (Palmowski and Muller, 2000). Pictures of the physically pre-treated food waste samples are shown in Figure 3-13.

Figure 3–11 Waring High Performance grinder used for milling of food waste samples

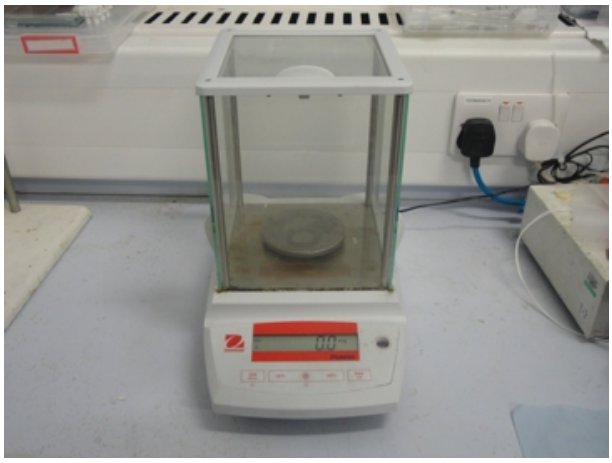


Figure 3–12 Ohaus PA64 Pioneer analytical balance used for precise measuring of the mass of dried and milled substrate samples

The excess samples were stored inside airtight plastic containers in cool dark cabinets to avoid absorption of moisture from the atmosphere. Freeze drying was not considered because it can lead to the disintegration of the plant material which can affect the results of anaerobic digestion (VDI, 2006).

As calculated in Section 3.5.1, the substrate quantity required for each digester batch was 8.4 g VS.

Figure 3–13 Pictures of dried and milled pre-treated Food Waste (a) Yam Peel (b) Cassava Peel (c) Cocoyam Peel and (d) Plantain Peel.

The sample quantity of food waste for the mono digestion tests was 8.4 g VS. For the co-digestion tests, the ratio of FW:WH used was 2:1 This ratio was selected because Water Hyacinth had a low Biogas Yield. In co-digestion in order to improve the overall gas yield of the co-substrates a higher percentage of the energy rich substrate should be utilised compared to the low energy substrate. Using the ratio FW : WH of 2:1 for the 8.4 g allocated to the substrate implies that the food waste and water hyacinth will have an amount corresponding to:

FW : WH = 2:1 = 5.6 : 2.8 (g VS)
The food waste content in the co-digested batches was 5.6 g VS while the water hyacinth content was 2.8 g VS. The individual amounts of samples for each food waste were determined below:

Yam Peel:

VS/TS of Yam Peel = 92.5%

- For mono-digestion:

Each batch requires 8.4 g VS of Yam Peel

9.1 g of dry Yam Peel contain 8.4 g VS (using VS/TS value).

- For co-digestion with Water Hyacinth in the ratio 2:1(VS):

Each batch requires 5.6 g VS of Yam Peel

6.0 g of dry Yam Peel contain 5.6 g VS (using VS/TS value).

Cassava Peel:

VS/TS of Cassava Peel = 94.1%

- For mono-digestion:

Each batch requires 8.4 g VS of Cassava Peel

8.9 g of dry Cassava Peel contain 8.4 g VS (using VS/TS value).

- For co-digestion with Water Hyacinth in the ratio 2:1(VS):

Each batch requires 5.6 g VS of Cassava Peel

5.9 g of dry Cassava Peel contain 5.6 g VS (using VS/TS value).

Cocoyam Peel:

VS/TS of Cocoyam Peel = 91.5%

- For mono-digestion:

Each batch requires 8.4 g VS of Cocoyam Peel

9.2 g of dry Cocoyam Peel contain 8.4 g VS (using VS/TS value).

- For co-digestion with Water Hyacinth in the ratio 2:1(VS):

Each batch requires 5.6 g VS of Cocoyam Peel

6.1 g of dry Cocoyam Peel contain 5.6 g VS (using VS/TS value).

Plantain Peel:

VS/TS of Plantain Peel = 90.8%

- For mono-digestion:

Each batch requires 8.4 g VS of Plantain Peel

9.2 g of dry Plantain Peel contain 8.4 g VS (using VS/TS value).

- For co-digestion with Water Hyacinth in the ratio 2:1(VS):

Each batch requires 5.6 g VS of Plantain Peel

6.2 g of dry Plantain Peel contain 5.6 g VS (using VS/TS value).

3.5.3 Water Hyacinth

This section describes the collection and processing of the water hyacinth plant.

Procedure

- Five kg of Water Hyacinth was obtained from Anglo Aquatic Plant, Enfield.
- The plant was rinsed to remove extraneous particles and then dried in a fume hood.
- The plant was then dried at $80^{O}C$ until constant weight was obtained.
- The dried sample was ground into a fine power using a high-speed mill with a grinding speed of 19,000 rpm.
- The milled sample was sifted through a 0.5 mm sieve.
- The processed samples were weighed and 2.8 g VS was kept for co-digestion tests. Excess samples was stored in an airtight container.

In full detail, the fresh water hyacinth was obtained from Anglo Aquatic Plant, Enfield, an agricultural nursery that specialises in aquatic plants. The sample preparation method was the same method used for preparing the food waste. A portion of the water hyacinth was tested to determine its Total Solid

and Volatile Solid content. The results indicated a Total Solids of 4.1%, Volatile Solid of 3.3% and VS/TS of 80%.

Based on calculations in Section 3.5.1, the mass of substrate for each digester batch will be 8.4 g VS shared between the food waste and the water hyacinth in the ratio 2:1. In Section 3.5.2 it was determined that the water hyacinth mass in the co-digested batches was 2.8 g VS. The mass of dry water hyacinth to be added to each co-digested batch is determined below:

VS/TS of Water Hyacinth = 80%

Each batch requires 2.8 g VS of Water Hyacinth

3.5 g of dry water hyacinth contain 2.8 g VS (using VS/TS value).

The picture of the physically pre-treated water hyacinth is shown in Figure 3-14.

Figure 3–14 Picture of dried and milled Water Hyacinth

3.5.4 Bio-Methane Potential Test

This section describes the bio-methane test performed on the samples to determine their biogas potentials. The procedure of this section lists the actions taken after the third Configuration system was set-up and the food and water hyacinth samples had been prepared for testing using their listed testing Procedures. This Bio-methane Potential test procedure occurs immediately after the inoculum treatment procedure.

Procedure

- The agitation of the water bath was turned off.
- Eight of the nine reactor vessels containing the treated inoculum were opened and 8.4 g VS of each sample was placed in them. The ninth vessel was left with only the inoculum.

- All the vessels were closed and shaken by hand, to homogenise the reactor contents, then placed back in the water bath.
- All the vessels were flushed with Nitrogen gas to create anaerobic conditions.
- The nine 500 ml inverted measuring cylinders were refilled with water.
- The agitation of the water bath was switched on again at 100 strokes per minute.
- Biogas production was recorded from the graduations of the measuring cylinder while pH values were recorded from the digital display of the pH meter. The methane and carbon dioxide content were automatically logged on the laptop.

In detail the bio-methane potential test was performed in line with the guidelines set by VDI 4630 (VDI, 2006) for standardized fermentation test. The nine vessels in the heating bath were used to perform the Bio-Methane Potential test in duplicates. There were four pairs of samples and one vessel serving as the blank test or zero sample. The vessels were washed and cleaned with isopropanol to eliminate any microorganisms that might contaminate the AD microbes. In the zero sample vessel, 500 g of inoculum was added to the vessel and sealed tight. In the mono-digestion vessels, the following amounts of food waste were added to 500 g of inoculum:

Yam Peel	- **9.1 g**
Cassava Peel	- **8.9 g**
Cocoyam Peel	- **9.2 g**
Plantain Peel	- **9.2 g**

In the co-digestion vessels, the following amounts of Food Waste and Water Hyacinth were added:

Yam Peel	- **6.0 g**	and	Water Hyacinth	-**3.5 g**
Cassava Peel	- **5.9 g**	and	Water Hyacinth	-**3.5 g**
Cocoyam Peel	- **6.1 g**	and	Water Hyacinth	-**3.5 g**
Plantain Peel	- **6.2 g**	and	Water Hyacinth	-**3.5 g**

These combinations provided a FW : WH of 2:1 (g VS) which in turn produced reactants with S:I ratios of 1:2 (g VS). These combinations will produces digester Total Solid contents below 10%, which meets the recommended VDI 4630 guidelines for Total Solids in a BMP test. It is also in line with (Steffen et al., 1998) who stated that for conventional CSTR digesters, the optimum Total Solid content should be in the range of 6-10%.

The vessels were then sealed with their lids to make them airtight. Next nitrogen was flushed through the vessels to create anaerobic environments. The vessels were then placed in the heated water bath, which was already

heated to 37^{O}C (310 K). Care was taken to ensure that the water level in the bath was always above the level of the reactants in the vessels. The shaking water bath was then set to shake at 100 strokes per minutes for agitation. An inline biogas analyser was connected to the co-substrate vessels. The analyser determined the percentage methane, propane and carbon dioxide in the biogas every 15 minutes during the BMP test period. Gas readings were taken twice daily for the first few days and then daily afterwards to make the course of gas formation recognisable. Cumulative flow graphs were drawn from that data to determine the gas production curves. pH readings were taken daily to analyse the pH levels of the solutions. The retention time was 20 days for each batch. That time was sufficient for the daily gas production rate to drop to less than 1% of the cumulative gas produced up to that moment which is in line with VDI 4630 guidelines. The biogas produced from the zero sample vessel was deducted from the biogas produced from the sample vessels in order to obtain the Specific Biogas Yield from the substrates.

3.6 Statistical Analysis

The various statistical analyses that were performed on the results are presented in this section. The analyses were performed using computer programmes, specifically IBM SPSS and Microsoft Excel.

3.6.1 Kruskal-Wallis Test

This test is a non-parametric alternative to the ANOVA test used when the assumptions of the parametric tests are not met. Such as when the variances are not equal or the results do not form a normal distribution.

3.6.2 Dunn's Test

This is a non-parametric post-hoc test that is used to determine the groups that have significant differences between them.

3.6.3 Non-Linear Regression

Non-linear regression is a form of regression analysis in which experimental data are modelled by a function, which is a nonlinear combination of the model parameters and depends on one or more independent variables. The analysis was used to fit the cumulative biogas production curves to the Modified Gompertz Model in order to obtain the process kinetic constants.

3.6.4 Coefficient of Determination R^2 and R^2_{adj}

The Coefficient of Determination (R^2) indicates the proportion of the variance in the dependent variable that is predictable from the independent variable. It gives an indication of the goodness of fit of a model by comparing how well the regression line approximates the real data points. The Adjusted Coefficient of determine (R^2_{adj}) is a modified version of (R^2) that takes into account the number of predictors in a model. They were both used to

compare the measured biogas values to the predicted values from the model.

3.6.5 Root Mean Square of Errors (RMSE)

RMSE measures the sample standard deviation of the differences between values predicted by a model and the experimental values. It was used to compare the biogas production values and the predicted values from the model.

3.6.6 Spearman's Rank Order Correlation

Spearman's Rank Order Correlation is a nonparametric measure of rank correlation. It can be used to assess the relationship between two ranked groups. The analysis was used to determine the relationship between the food waste characteristics and their theoretical Bio-Methane Potentials.

3.7 Error Analysis

This section analyses the various errors that could result from performing the various tests.

3.7.1 Systematic Errors

Systematic errors are errors that affect the accuracy of measurements taken in an experiment. Common types can be from faulty calibration of measuring instruments or faulty reading of measuring instruments. In this study, the instruments were properly calibrated as evidenced by certificates of calibration. As for faulty reading of instruments, all the components, with the exception of the measuring cylinder, had digital outputs. This prevented any error from reading the measured values. In the case of the measuring cylinder, there was the possibility of parallax error.

3.7.2 Random Errors

Random errors are errors that affect the precision of a measurement. These errors are random and can vary between tests. They can result from extraneous disturbances in the form of noise. These errors are unavoidable but replicating tests can reduce them.

3.7.3 Accuracy

Accuracy measures how close a measured value is to its true or accepted value. In the case of this study, the true values for the biogas potential of the samples are unknown due to absence of past studies on the samples. Additionally such biogas yields from the same type of substrate can vary widely based on different experimental procedures between tests. The accuracy of the various components are listed below:

Gas Analyser	± 0.01%
pH meter (Hanna)	± 0.2
Weight scale	± 0.01 g

3.7.4 Precision

Precision measures how closely two or more measurements agree with each other. In the case of this study, the precision was measured by replicating the experiments. The error bars in the graphs were used to indicate the precision between the replicate tests.

3.7.5 Propagation of Errors

The results of the experiments were calculated from several measurements that have potential systematic errors. Each of these errors is propagated to the final result.

In the case of the cumulative biogas yields, each of the gas measurements from the water displacement cylinder has a maximum error of ± 0.3 ml. This error was propagated to the final biogas yield of each substrate. The error for the final result will be the square root of the sum of the squares of each error (Taylor, 1982). For the 25 measurements (2 daily for the first 5 days and 1 for each remaining 15 days) the propagated error is ± 1.5 ml. For the methane and carbon dioxide content of the biogas, 96 readings were taken each day, with an uncertainty of ± 0.01%. Using the same method as above, the propagated daily error is ± 0.1%.

The pH readings and mass of the food waste were measured directly without any calculation, leading to no propagation of errors.

3.8 Chapter Summary

This chapter presented the experimental methods used in determining the findings of this study. The food samples were obtained from the Ridley Road Food Market, London, while their wastes were extracted using similar Niger Delta food processing methods. The Specific Waste Index was determined by weighing both the food waste and the consumable part of the food and then calculating the SWI.

The food wastes characterisations were performed using standard methods for measuring Total Solids, Volatile Solids, Crude Fibre, Protein, Fat, Nitrogen Free Extracts, Ash, and Moisture content. The tests were performed at NRM Laboratories, Bracknell, UK. The Theoretical Bio-Methane Potential for each sample was calculated using the results from the food wastes characterization inputted in the Baserga Model.

The Food Waste Quantification and Bioenergy Potential of the samples were estimated using the food consumption frequency of the local population and the waste and bio-methane potentials of the food waste samples.

Three bioreactor configurations were designed and would be tested for energy consumption and effectiveness in performing BMP tests. The first two Configurations are single batch reactors, with the Second Configuration more

advanced with data logging capabilities. The Third Configuration is a multiple batch configuration system that can simultaneously perform nine anaerobic digestion tests.

The Bio-Methane Potential tests were performed using the VDI 4630 guidelines as standard process parameters. The tests were performed on four of the most common food wastes in the Niger Delta, which are yam, cassava, cocoyam, and plantain peels co-digested with water hyacinth. The inoculum for the tests was obtained from an Anaerobic Digestion plant at Camley Street Natural Park, London. The digester has been running for over 2 years and is fed catering food wastes from local canteens and offices. The inoculum was degassed for a week prior to the BMP tests to create a hunger phase and help the microbes adapt to the new environment. The food wastes and water hyacinth samples were dried and milled and then added to the pre-treated inoculum, which began the BMP test. The retention time for the test was 20 days while the agitation was achieved by via a shaking water bath at 100 strokes per minute and temperature of $37^{O}C$.

Statistical analysis for significant differences between results was performed using non-parametric tests of Kruskal-Wallis and Dunn's test. Other statistical tests used were Non-Linear Regression and Co-efficient of Determination to determine the relationship between the measured and simulated results. The error analysis identified the systematic and random errors of the system.

This chapter presented detailed descriptions of the experiments that were performed to achieve the various aims of this study, ranging from the various foods' waste content and characterisation to quantification of waste in the Niger Delta. Methods for designing various reactor configurations were also presented. The chapter ended with a full description of the Bio-Methane Potential tests that were used to determine the biogas yields of the food waste. The next chapter presents the results from the experiments described in this chapter.

Chapter 4 Results and Discussion: Waste Characterisation, Quantification and Energy Potential

The previous chapter described the methods used for the various experiments of this study. This chapter presents the results and discussions of those experiments and the analysis of the data. The waste content and characterisation results are presented for nine food waste in addition to their regional energy potential. Next the theoretical BMP of the samples are calculated and the regional waste and energy potential are estimated.

4.1 Waste Content of Selected Food Items

This section presents nine common foods in the Niger Delta region and the analysis of their unavoidable food waste content. The data was used to prepare a Specific Waste Index table. The food waste content of the foods and the organic portion of the food waste were also discussed in this section. In order to generate the type of wastes that digesters in the Niger Delta would utilise, the food wastes were extracted by local methods.

4.1.1 Results

The Specific Waste Index (SWI) of the food samples were determined using Equation (8). The data showed an SWI range of 0.2 – 1.5 for the nine food waste with an average value of 0.5. The results indicated that corn had the highest SWI range of 1.4-1.5 while egusi had the lowest value at 0.2. The tubers and plantain had values between 0.3 and 0.5 with plantain and cassava at the upper and lower end respectively. The results of the average SWI for the nine samples are presented in Table 4-1. The waste contents of each food and their organic content (OWC/TWC) are displayed in Figure 4-1. The average total waste content of the nine food items is 29% while the average organic waste content of the foods is 9%. Corn has the highest waste content of 59% from the husk and cob. The corn wastes have a low organic content of 30%. Ugwu has the second highest waste content of 37% while the ugwu stalk has the lowest organic content of 2%. The lowest waste content is from egusi at 18% but the egusi shells have the highest organic content at 80%. Groundnut Shell has the second highest organic content of waste at 78% while the groundnut has a low waste content of 19%. Within the group of plantain and tubers, plantain has the highest waste content of 34% while cassava has the least at 20%. When considering the organic content of the food waste, yam has the highest at 34% while plantain has the lowest at 14%.

From the results of the tests, the food items can be ranked from highest to lowest waste content:

Corn > Ugwu > Plantain > Yam > Groundnut > Cocoyam > Beans > Cassava > Egusi

When considering the organic fraction of the waste, ranking becomes:

Egusi > Groundnut > Yam > Corn > Cassava > Cocoyam > Beans > Plantain > Ugwu

Table 4–1 Specific Waste Index of common Niger Delta foods from highest to lowest value

Food	Food Waste	Specific Waste Index
Corn	Corn cob and husk	1.5
Ugwu	Ugwu stalk	0.6
Plantain	Plantain Peels	0.5
Yam	Yam Peels	0.3
Cocoyam	Cocoyam Peels	0.3
Groundnut	Groundnut shell	0.3
Beans	Beans skin	0.3
Cassava	Cassava Peels	0.3
Egusi	Egusi shells	0.2

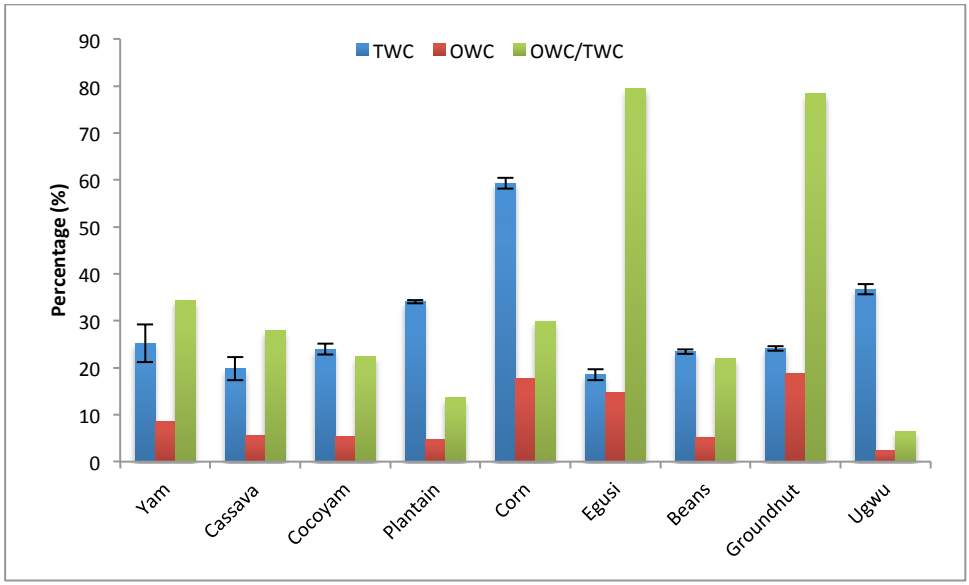


Figure 4–1 Waste content of nine Niger Delta foods (TWC error bars indicating relative error of measurement)

TWC Total Waste Content
OWC Organic Waste Content

4.1.2 Discussion

Corn had the highest SWI value and was the only sample whose value was higher than 1.0. This indicated that it was the only food item which produced more waste than consumable parts. A contribution to this high value is the retained moisture in the cob from the processing method it underwent. Other food preparation methods such as roasting of corn might lead to a lower

waste content. Despite its high waste content, corn is the fourth ranked when the organic content of its waste is considered.

Yam and cassava had high variations in waste content due to the differences in the sizes of the individual tubers and the varied thickness of their peels. Plantain had the least variations possibly as a result of the similar sizes of the samples in addition to the peels being removed without bits of the fleshy parts. Beans and groundnuts also had low variations in waste content. Similar to plantain, their waste extraction processes do not take off any fleshy part of the food item so the wastes have the tendency to be uniform. The SWI values for the three tubers are close to the SWI range measured for another ground crop, potato at 0.3-0.5 (Russ and Meyer-Pittroff, 2004). Results from the same study by Russ and Meyer-Pittroff showed that oats, which are physically similar to egusi seeds, have an SWI of 0.4 which is higher than the value of 0.2 for Egusi. Egusi has the least amount of total waste with a value of 19%, which is 11% points less than the average value. The seed has a low moisture content leading to dry and lightweight shells. The total waste content of beans was 23% and consisted of moisture from its processing method. The results show that foods like Corn, Plantain and Ugwu can have high waste contents but the waste will consist of low organic fractions. However foods like Egusi and Groundnut have low waste contents which have high organic proportions.

The results of Russ and Meyer-Pittroff (2004) showed that the only food whose SWI was greater than 1.0 was cheese, whose values got up to 11.3 for whey waste as a result of its processing method. None of the samples of this study obtained an SWI value as high as 2.0. Foods with high SWI are ideal for feedstock that will be considered in the anaerobic digestion chain. If SWI is the only factor, corn produces the best results. However the organic content of the food waste has to be considered as well. This makes egusi the ideal choice. The implication is that both factors have to be considered when selecting an appropriate food for its waste. Both factors will provide important data in relation to any application of the wastes as AD feedstock.

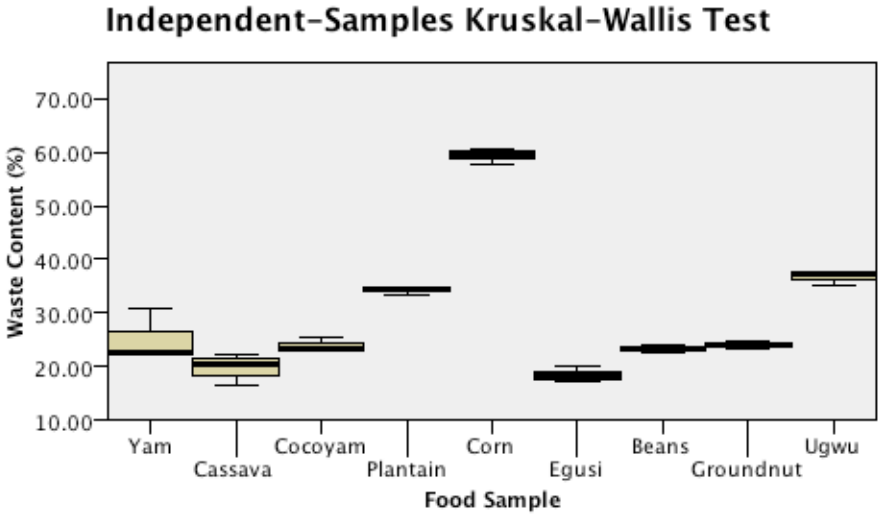
In the UK, unavoidable food waste such as the ones analysed above account for 19% of the total annual food waste in the country. 26% of all food waste comes from vegetables which are similar to the ones above with 82% of the vegetable wastes as either unavoidable or potentially avoidable waste (WRAP, 2008).

4.1.3 Statistical Analysis

The experiments had small sample sizes (n=3) due to the cost limitation in performing numerous replications of waste content tests. Due to the small sample size of the groups, the distribution of the data cannot be verified to be normal. Hence a non-parametric Levene's test was used to test the equality

of variances in the samples (homogeneity of variance). The results indicated that there was no homogeneity of variance ($p<0.05$). Additionally a visual analysis of the variance of the groups in Appendix 9 showed that they were unequal. The results indicated that one of the assumptions of common statistical parametric tests was not met, therefore a non-parametric Kruskal-Wallis test was performed on the results to determine if there was any significant difference between the samples.

The results of the Kruskal Wallis test indicated a significant difference between the samples ($p>0.05$). The results are shown in Figure 4-2.



Total N	27
Test Statistic	23.450
Degrees of Freedom	8
Asymptotic Sig. (2-sided test)	.003

1. The test statistic is adjusted for ties.

Figure 4–2 Kruskal-Wallis Analysis of Food Waste Content

The test did not show which samples were significantly different from each other. Hence a non-parametric post hoc Dunn's test was performed to identify those significantly different groups. The results showed that there was significant different between various samples. The results are presented in Figure 4-3.

	Yam	Cassava	Cocoyam	Plantain	Corn	Egusi	Beans	G-nut	Ugwu
Yam		0.328	0.758	0.150	0.018	0.237	0.837	0.572	0.057
Cassava			0.198	0.016	0.001	0.837	0.237	0.123	0.004
Cocoyam				0.258	0.040	0.136	0.918	0.797	0.111
Plantain					0.355	0.009	0.217	0.382	0.643
Corn						0.000	0.031	0.072	0.643
Egusi							0.165	0.080	0.002
Beans								0.719	0.090
Groundnut									0.181
Ugwu									

Figure 4–3 Dunn's Non-parametric Post-Hoc test result showing samples with significant differences in green.

The statistical analyses were performed using the SPSS IBM software package and test statistics are presented in Appendix 10.

4.2 Food Waste Characterisation and Bio-Methane Potential Results

The previous section presented the common Niger Delta foods and their waste content. This section presents and discusses the food waste characterisation and theoretical Bio-Methane Potential of the nine food wastes and Water Hyacinth.

4.2.1 Results of Food Waste Characterisation

Results from the characterisation revealed that the Total Solid content varied widely between samples. The values ranged from 7% – 82% with an average value of 34%. Egusi shell and groundnut husk had the highest TS values of 82% and 81% respectively. Their TS values are 48 percentage points higher than the average of the group and 45 percentage points higher than the third highest item, which is Yam Peel at 37%. Water hyacinth and ugwu stalk had the lowest Total Solid contents at 7%. They were 26 percentage points lower than the average of the group. For the tubers and plantain their TS values ranged from 15 - 37%. In that group yam peel had the highest TS content while plantain peels had the lowest. Results of the VS/TS analysis showed that values ranged from 84% for water hyacinth to 97% for egusi shell and corn waste. In the tubers and plantain category, cassava peels had the highest VS/TS of 96% while plantain peels had the lowest at 88%.

Crude protein values ranged from 6% of egusi shell to 37% for ugwu stalk with an average value of 13%. Of the tubers and plantain, cocoyam peels had the highest value at 11% with plantain peels at the lower end with 7%. Crude fibre had an average value of 29% within the group with a range from 7% for yam peel to egusi shell at 82%. Cocoyam peels had the highest fibre content of the tubers. The oil content of the foods were low with the exception of cassava peels which had an oil content of 25%. The Nitrogen

Free Extracts made up the highest nutrient proportion in 80% of the samples. The value was as high as 82% for yam peels with a low value of 11% for egusi shells. The group average was 52%. Water hyacinth and ugwu stalk had the highest ash contents at 17% and 13% respectively. The characterisation results of the samples are presented in Table 4-2. The ranking of the food samples in relation to their various characteristics are shown in Table 4-3. The ranking allows for a comparative analysis between the different foods based on nutrient content.

4.2.2 Discussion of Food Waste Characterisation Results

The results from the TS analysis showed a high variation in TS content across the samples. All values, with the exception of water hyacinth and ugwu stalk, were within the TS range of plant waste and by-products as reported by Al Seadi et al. (2013). Egusi shell and groundnut husk had the highest values, and their TS values fell within 70%-90% which is the TS range for straw. The TS for groundnut husk was lower than the 95% obtained by Osman et al. (2006) but higher than the 70% obtained by Jekayinfa and Omisakin (2005). The low amount of moisture in egusi shells

Table 4–2 Characteristics of Water Hyacinth and nine (9) Niger Delta food waste showing nutrient and moisture content obtained from this study

Food Waste	Water Hyacinth	Yam Peels	Cassava Peels	Coco yam Peels	Plantain Peels	Corn cob & husk	Egusi shell	Bean skin	Ground nut Husk	Ugwu Stalk
Total Solids (%)	7.2	36.6	29.3	24.5	15.4	30.7	81.9	22.8	81.3	7.5
Volatile Solids (% TS)	83.3	93.7	95.6	91.4	88.3	97.1	97.1	96.5	96.4	86.7
Crude Protein (% VS)	20	9.6	8.6	10.7	7.4	10.1	5.7	16.8	6.8	36.9
Crude Fibre (% VS)	20	7.0	8.2	12.1	8.8	21.8	81.6	28.2	79.5	29.2
Oil-B (% VS)	<5	1.2	24.6	1.8	4.4	11.7	1.3	1.4	<0.4	<4.6
Nitrogen Free Extract (% VS)	55	82.2	58.6	75.4	79.4	56.4	11.4	53.6	13.4	29.2
Ash (% TS)	16.7	6.3	4.4	8.6	11.7	2.9	2.9	3.5	3.6	13.3
Moisture (%)	92.8	63.4	70.7	75.5	84.6	69.3	18.1	77.2	18.7	92.5

Table 4–3 Ranking of Food Waste Characterisation with 1 highest and 10 lowest

Rank	Total Solids	Moisture Content	VS	VS/TS	Crude Protein	Crude Fibre	Oil B	NFE	Ash
1	ES	WH	ES	ES/CCH	US	ES	CP	YP	WH
2	GH	US	GH	BS	WH	GH	CCH	PP	US
3	YP	PP	YP	GH	BS	US	WH	CoP	PP
4	CCH	BS	CCH	CP	CoP	BS	US	CP	CoP
5	CP	CoP	CP	YP	CCH	CCH	PP	CCH	YP
6	CoP	CP	CoP	CoP	YP	WH	CoP	WH	CP
7	BS	CCH	BS	PP	CP	CoP	BS	BS	GH
8	PP	YP	PP	US	PP	PP	ES	US	BS

9	US	GH	US	WH	GH	CP	YP	GH	ES/CCH
10	WH	ES	WH		ES	YP	GH	ES	
Average (%)	33.7	66.3	32.05	92.6	13.2	29.6	5.6	51.5	7.4

and groundnut husk is caused by the drying process they undergo prior to being sold at the market. Water hyacinth had the lowest TS, with the value in between 5% and 9% obtained by Chynoweth et al. (1982) and Chanakya et al. (1993). Feedstocks having high TS content like egusi shell and groundnut husk require additional water when digested. They also change the fluid dynamics of digesters leading to process failure. This is caused by bad mixing behaviour, solids sedimentation, clogging and scum layer formation (Steffen et al., 1998). Feedstocks with low TS values like water hyacinth and ugwu stalk increase digester volume with a low nutrient concentration. They also raise the heat input per m^3 of feedstock required, resulting in unfavourable process economics (Steffen et al., 1998). With the exception of the samples with very high and low values, the remaining samples have moderate TS values.

The VS/TS analysis resulted in a narrow range of values, ranging from 84% to 97%. The results were within the range of VS/TS for plant waste as reported by Al Seadi et al. (2013) and higher than the 70-80% for energy crops as reported by Neureiter (2013). Common biodegradable organic matter should have a VS/TS of 70% and above while feedstocks with lower than 60% VS/TS are not suitable as substrates for the AD process (Steffen et al., 1998). Water hyacinth and ugwu stalk had the lowest VS/TS contents at 83% and 87% respectively but are still within the acceptable values. The volatile solid content of a feedstock can be useful in bioenergy estimations but it does not give information on the digestibility of the sample (Drosg et al., 2013).

The yam peel TS content was higher than the values obtained by Ojikutu and Osokoya (2014), Makinde and Odokuma (2015) and Heiske et al. (2015) which ranged from 19% to 23% TS. For cassava peel, the TS of 29% and VS/TS of 96% were within the ranges of 25%-35% TS and 90%-97% VS/TS of Cuzin et al. (1991) and Jekayinfa and Scholz (2013). For the cocoyam peel, the 25% TS and 91% VS/TS was close to the 27% TS and 92% VS obtained by Adeyosoye et al. (2010) while for plantain peel, the low values for TS of 15% was close to the 13% of Makinde and Odokuma (2015) and 15% of Ojikutu and Osokoya (2014).

The green plants had the highest amount of crude proteins with ugwu stalk at 37% and water hyacinth at 20%. The results of Cheng et al. (2010) showed that water hyacinth leaves had the highest amount of crude protein at 21% while the roots had the lowest at 3%. The driest waste samples, egusi shell

and groundnut husk, had the lowest amounts of crude protein. Groundnut husk's protein content was close to the 5% obtained by Jekayinfa and Omisakin (2005). High amounts of protein in a feedstock can lead to high ammonia concentrations in the digester. The driest samples had the highest amount of crude fibre (cellulose, hemicellulose and lignin). The lowest values were below 9% for yam and cassava peels. Jekayinfa and Omisakin (2005) also obtained very low values of crude fibre for yam peels at 3%. High fibre feedstock can cause foaming and lignin incrustation in digesters.

Cassava peel, with a large margin, had the highest oil content at 25%. The high value is a result of the cassava tubers being covered in wax to prevent them from undergoing degradation caused by air oxidation, fungal attacks and loss of moisture (Booth, 1973; Knoth, 1993; Onyenwoke and Simonyan, 2014). High oil content leads to longer retention times due to their poor bioavailability (Steffen et al., 1998). The lowest values of 0.4% were from the groundnut husk, which is far lower than the 3% obtained by Jekayinfa and Omisakin (2005). These results contrast with the high crude oil content of the nut itself at 49% (Jiang et al., 2010). Excess oils in feedstock can have a detrimental effect during digestion due to oils poor water solubility and high VFA levels leading to low pH.

The yam peels had the highest NFE content while the lowest was the Egusi shells. The high NFE for Cocoyam peels at 75% was close to the value in literature of 72% obtained by Adeyosoye et al. (2010). For cassava peels, the NFE at 59% was very close to the 56% obtained by Aro et al. (2010). Water hyacinth had the highest ash content of 17%. This can be explained by the roots having a high affinity for accumulation of metals (Weis and Weis, 2004; Abdel-Sabour and Abdel-Haleem, 1996; Vesk et al., 1999). A study by Cheng et al. (2010) showed that ash content was highest in the roots of water hyacinth at 50% while lowest for the leaves at 13%.

4.2.3 Results of Theoretical Bio-Methane Potential

The results of the theoretical Bio-Methane Potential analysis showed a narrow range of (540 – 619) x 10^3 m^3/kg VS for biogas yields. The methane content varied between 51% – 58%. The biogas potentials are within the range of biogas yields of corn, barley, crude glycerine and wheat grains as reported in NNFCC (2016). Cassava peel has the highest potential yield at 619 x 10^3 m^3/kg VS and also the second highest methane content at 57%. The lowest potential biogas yield is from ugwu stalk at 540 x 10^3 m^3/kg VS but the sample has the highest methane content at 58%.

The biogas potentials for the fresh weight of the sample took into consideration the moisture content of the food waste. In this category, there was a high variation in potential yield, ranging from 33 - 460 m^3/t FW with an average potential of 184 m^3/t FW. The highest potential yields were from the

egusi shell and groundnut husk at 460 and 450 m^3/t FW respectively. They also have the lowest methane contents of 51%. The lowest potentials in this category were from the water hyacinth and ugwu stalk with biogas potentials of 33 and 35 m^3/t FW respectively and consisted of the third and highest methane contents of 55% and 58% respectively. For the tubers and plantain, yam peel has the highest potential at 188 m^3/t FW followed by cassava peels at 173 m^3/t FW. Next was cocoyam peels at 124 m^3/tonne and lastly plantain peels with the least potential at 76 m^3/tonne. The theoretical biogas yields on the volatile solid and fresh weight basis are presented in Figure 4-4.

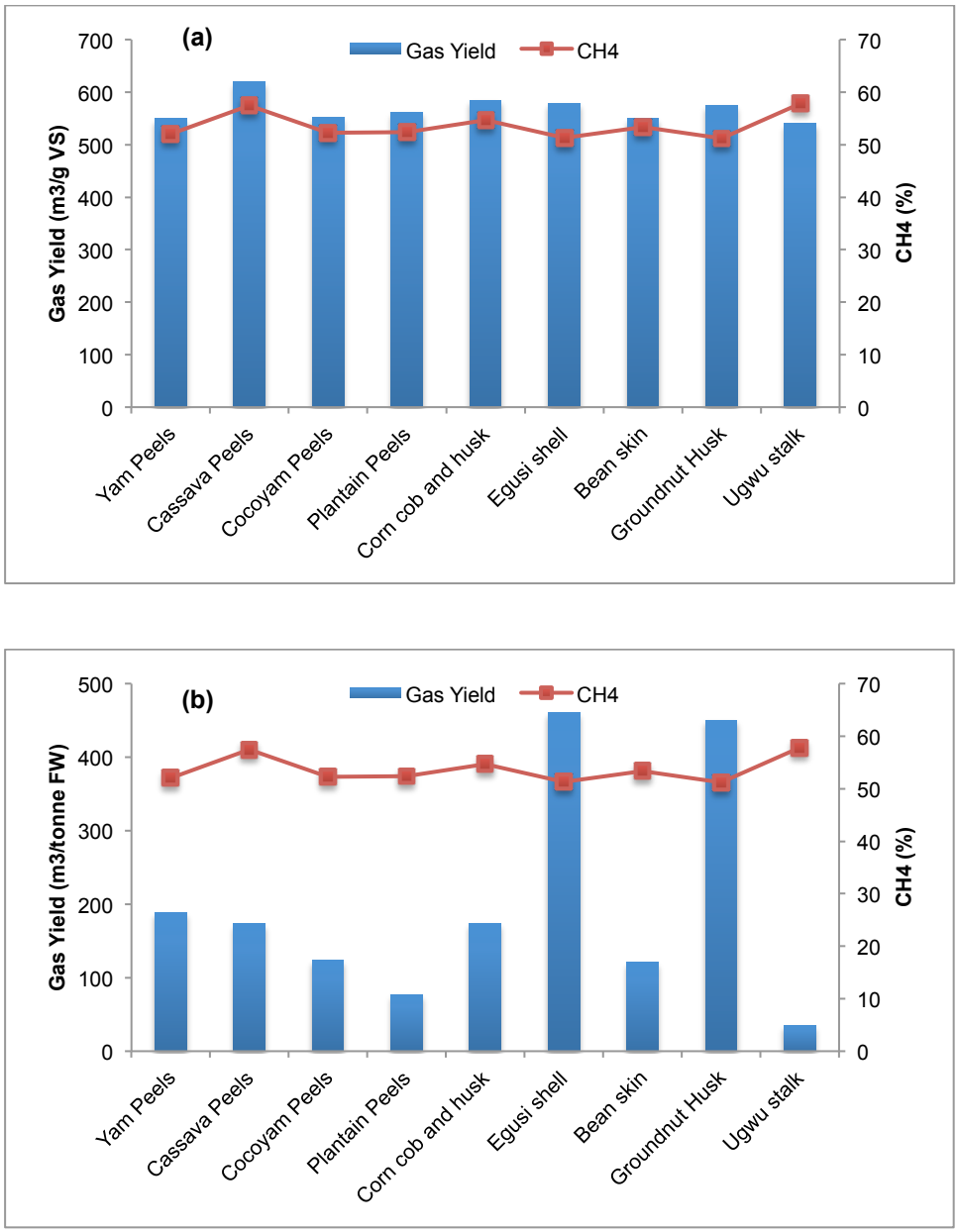


Figure 4–4 BMP for Water Hyacinth and (9) food waste in terms of (a) Volatile Solid and (b) Fresh Weight

4.2.4 Discussion of Theoretical Bio-Methane Potential Results

The theoretical biogas yields on a volatile solid basis present the biogas potential of the feedstock on a volatile solid basis. The yield on a fresh weight basis presents the theoretical results of yield from the wet weight of the sample. Cassava peel had the highest biogas potential and the second highest methane content. On a fresh weight basis it has the fifth highest yield. Its high moisture content at 71% causes a low nutrient concentration in a digester leading to lower energy output. The substrates with the highest moisture content, water hyacinth and ugwu stalk, had the lowest fresh weight biogas yields. They also had the third and highest methane contents of 55 and 58% respectively. However the low moisture contents of egusi shell and groundnut husk at 18 and 19% respectively, allow them to have the highest fresh weigh yields. Despite their high yields, they have the lowest methane contents of 51%. For the tubers and plantain, yam peel has the highest fresh weight biogas potential followed by cassava peel. Next was cocoyam peel while plantain peel has the least potential at 76 m^3/tonne.

The range of results for biogas yields on a volatile solid basis corresponds to a wide variety of feedstock found in literature. Feedstock with similar yields include vegetable waste, potato waste, food waste, fruit waste, slaughterhouse waste and household waste as reported by Deublein and Steinhauser (2011). This signifies that the biogas potentials of Niger Delta food waste are within the range of values from conventional feedstock. This makes them suitable candidates for anaerobic digestion feedstock. Actual biogas yields will be lower than their theoretical values due to the presence of non-degradable material. Furthermore microbes consume 3-10% of the substrates for their growth (VDI, 4630). The nine food wastes including water hyacinth fall into the category of plant based feedstock. Drosg et al. (2013) reported that the actual yields of such plant based feedstock are 50-70% of their theoretical values.

Comparing the study's results with fresh weight biogas potentials reported in Korres et al. (2013) the yield of water hyacinth was higher than the reported 15 m^3/tonne. Egusi shell and groundnut husk had higher yields than barley, rye, sugar beet and rice straw which ranged from 157 - 267 m^3/tonne. The closest samples to this lower range were the tubers. Egusi shell and groundnut husk had yields that were within the range of 400-500 m^3/tonne for paper co-digested with chicken manure. The results of Corn Cob and Husk were higher than the reported value for corn at 107 m^3/tonne. The food wastes and water hyacinth were ranked based on their biogas yields and are presented in Table 4-4.

The rankings of the food waste characteristics were compared to the rankings of the biogas yields to determine if there was a correlation between any of them. The Spearman's Rank Order Correlation was used for the

analysis and was implemented by IBM SPSS. The calculated correlation coefficients are presented in Table 4-5. From the results, there was a perfect correlation between the fresh weight biogas yields and the TS and VS content. There was also a strong relationship with the VS/TS ranking. This implies that the TS or VS content of feedstock can be used to determine which feedstock will produce more biogas when comparing more than one sample.

Table 4–4 Ranking of samples based on biogas yields and methane content (1 being highest and 10 being lowest)

Rank	Biogas Yield (VS)	Biogas Yield (FW)	Methane Content
1	CP	ES	US
2	CCH	GH	CP
3	ES	YP	WH
4	GH	CCH	CCH
5	PP	CP	BS
6	WH	CoP	PP
7	CoP	BS	CoP
8	BS	PP	YP
9	YP	US	ES
10	US	WH	GH
Average Value	566	184	54

For the biogas yield on VS basis, there was a moderate relationship with the TS and VS content. Methane content had a strong correlation with moisture and oil content of the feedstock. They are not perfect relationships, so they should be used cautiously when estimating which feedstocks have higher methane contents.

Table 4–5 Spearman's Rank Order Correlation Coefficients comparing the ranking of BMP results and nutrient content

	TS	MC	VS	VS/TS	CrP	CrF	Oil	NFE	Ash
Biogas (FW)	1.0	-1.0	1.0	0.8	-0.8	0.2	-0.5	-0.2	-0.8
Biogas (VS)	0.4	-0.4	0.4	0.1	-0.4	-0.0	-0.4	0.2	-0.3
Methane	-0.7	0.7	-0.7	-0.6	0.4	0.2	0.7	0.3	0.5

4.3 Food Waste Quantification and Bioenergy Potential of Niger Delta.

The previous section presented the results of the characterisation and bio-methane potential of Niger Delta food waste. This section presents an estimate of the regional food waste potential of the Niger Delta foods based on food consumption patterns. Also estimated was the regional bioenergy potential from the food waste. The **Bioenergy Potential** of food waste is the prospective work that can be performed when the nutritious contents of the waste are harnessed and converted to energy. The regional waste

production from the nine foods were calculated using food consumption data and food waste content already identified in Section 4.1. The regional consumptions of the foods were calculated using the food consumption frequency of the food items from Ene-Obong et al. (2013).

4.3.1 Results of Waste Quantification

The waste quantification results were presented for eight foods because consumption data could not be obtained for ugwu. Corn had the highest waste potential at 590 -1200 (10^3 tonnes/yr) while egusi had the lowest potential of 62 - 120 (10^3 tonnes/yr). The regional waste potential from the eight foods is 2,600 – 4,100 (10^3 tonnes/yr). The annual waste potential from the Niger Delta foods are presented in Figure 4-5. The results are a conservative estimate because the study of Ene-Obong et al. (2013) indicated that some individuals consumed the food items more than once a day and that the data represented 70% of the population. The assumption used in this study for the waste estimation was that the food items were consumed only once a day.

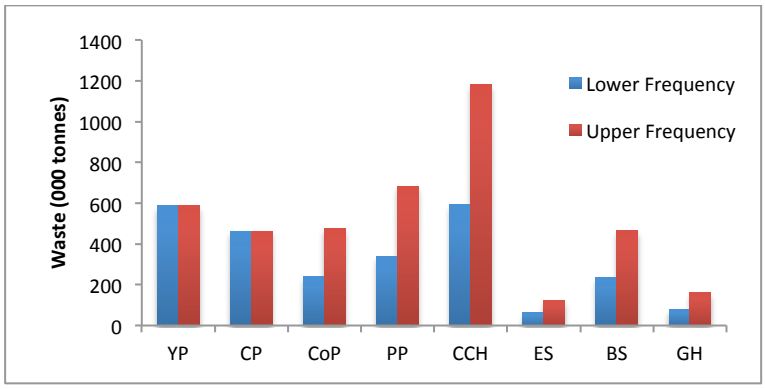


Figure 4–5 Annual waste production of 8 common Niger Delta foods determined in this study showing the lower and higher waste potentials based on low and high feeding frequency

4.3.2 Discussion of Waste Quantification

Corn has the highest waste potential despite not being consumed as much as yam or cassava. This was a result of its high waste content. Egusi will produce the least amount of waste as a result of its low waste content and low consumption frequency. Of the eight food items, the most consumed foods per person were yam and cassava at 73 kg per annum each. The least consumed foods were groundnut and egusi, both at 10 - 21 kg per annum. When the waste contents and regional population are factored in, corn leads the group producing 590 – 1,200 (10^3 tonnes/yr) of waste. Egusi retains the lowest position producing 62 -120 (10^3 tonnes/yr) of waste. For the tubers and plantain, the lower frequency of cocoyam produces the lowest waste at 230 (10^3 tonnes/yr) while the upper frequency of plantain produces the highest at 680 (10^3 tonnes).

In the UK, research by WRAP (2009) showed that at the household level, unavoidable wastes from fruits and vegetables totalled 520,000 and 250,000 tonnes/yr respectively. These two food groups represent the wastes in this study. Their research also showed that other root vegetables, which could represent the tubers in this study, produced a total of 23,000 tonnes/year of unavoidable waste. This is far lower than the output from the tubers in this study which range from 240 - 590 (10^3 tonnes/yr). Bananas, which are similar to plantains, produced 230,000 tonnes/yr of waste in the UK, which is less than the range of 340 – 680 (10^3 tonnes/yr) of plantain waste for the Niger Delta. In the UK corn produced 18,000 tonnes/yr of waste, which is far lower than the 590 -1,200 (10^3 tonnes/yr) of the Niger Delta. Beans produced 6,000 tonnes/yr of waste in the UK, which is far lower than the 230 – 470 (10^3 tonnes/yr) of this study. The highest amount of unavoidable food waste in the UK was tea waste at 370,000 tonnes/yr. The high variability between the results from the Niger Delta and the UK is a result of differences in food preference. Another factor is that in the Niger Delta, food is predominantly prepared from scratch, whereas in the UK, the foods are bought already processed with little to no waste.

4.3.3 Results of Bioenergy Potential of the Niger Delta

The regional projected biogas yield from the Niger Delta is 442 – 693 (10^6 m^3/yr) and is represented graphically in Figure 4-6. The total energy to be derived from the biogas would be 2.5 – 3.9 TWh/yr. Corn has the highest potential biogas yields of 103 – 206 (10^6 m^3/yr) with a methane yield of 56 – 113 (10^6 m^3). The lowest yield is from Plantain Peel at 26.0 – 52.0 (10^6 m^3/yr) with a methane yield of 14 – 27 (10^6 m^3/yr). For the tubers and plantain, yam peel produces the highest amount of biogas at 111 (10^6 m^3) while the lower limit of plantain produces the lowest at 26 (10^6 m^3). The bioenergy potentials are presented in Table 4-6.

Table 4–6 Renewable Energy Potential of the Niger Delta from food waste as determined in this study

Food Waste	YP	CP	CoP	PP	CCH	ES	BS	GH
Annual Waste (10^5 tonnes/yr)	5.9	4.6	4.8 - 2.4	6.8 - 3.4	11.8 - 5.9	1.2 - 0.6	4.7 - 2.3	1.6 - 0.8
Biogas Yield of FW ($10^2 m^3$/t)	1.9	1.7	1.2	0.8	1.7	4.6	1.2	4.5
Annual Biogas (10^8 m^3/yr)	1.1	0.8	0.3 -0.6	0.3 -0.5	1.0 -2.1	0.3 -0.6	0.3 -0.6	0.4 -0.7
Total Methane Content (%)	52	57	52	52	55	51	53	51
Annual Methane (‘10^6 m^3/yr)	57.5	45.9	15.4-30.9	13.6-27.3	56.4-112.8	14.5-29.1	15.1-30.1	18.5-37.0
Energy Potential (GWh/yr)	610	480	160-330	140-290	590-1,200	150-310	160-320	190-390

Gross Calorific Value of Methane= 38 MJ/m^3
1 MJ = 0.2778 kWh

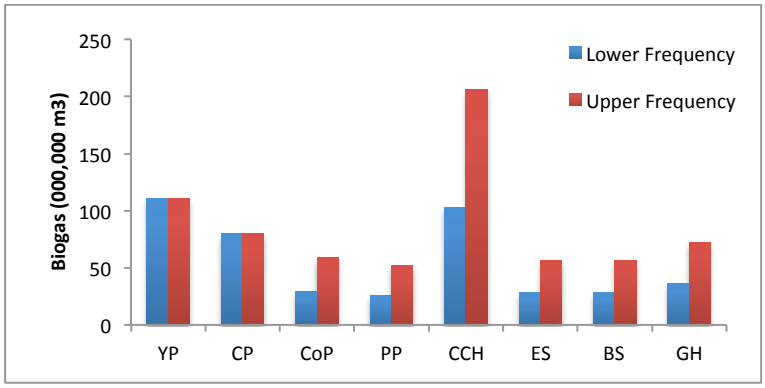


Figure 4–6 Annual Biogas Potential of the Niger Delta determined from this study

4.3.4 Discussion of Bioenergy Potential of the Niger Delta

Some of the food items such as plantain peel had a high amount of waste but when their biogas potential was factored in, they became less productive. Cocoyam peel had a lower waste production compared to plantain peel but when all the factors were considered, the cocoyam peel has a higher energy potential. Corns cob and husk contributes the most to the energy mix at 31% while the least contribution is from Plantain Peel at 7%. The tubers and plantain contribute a total of 43% to the mix. The contribution of each waste to the energy mix is presented in Figure 4-7.

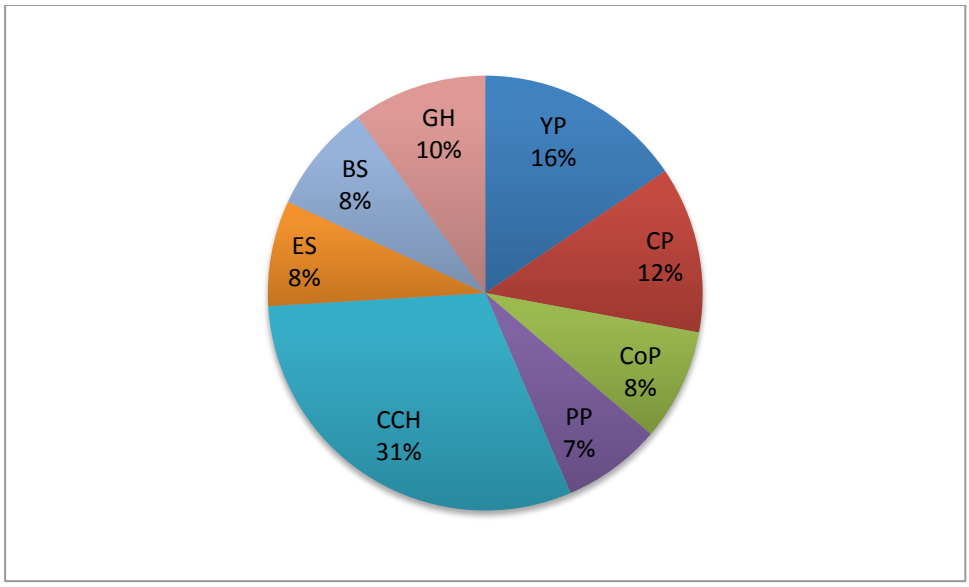


Figure 4–7 Contribution of each food waste to the total Bioenergy Mix (upper limits) for common Niger Delta foods

The projected maximum electricity demand of Nigeria for 2020 at 7% growth is 399 TWh/yr (REMP, 2012). The bioenergy generated from the Niger Delta food waste is 3.9 TWh/yr and would meet 0.9% of that projected power demand. When considering the long-term projections (2021-2030) for electricity from biomass of 0.9 TWh/yr (REMP, 2012), that projection would be surpassed by 333%. Considering more recent statistics, the potential

bioenergy of this study is 1/8 times the total generated electrical energy in Nigeria for 2014, which was 29.7 TWh (GOPA, 2015). Based on Nigeria's electricity consumption per household of 655 kWh/yr (WEC, 2016), the bioenergy would meet up to the demand of 5.9 million households. This represents 88% of the households in the Niger Delta. Using the Nigerian per capita electricity consumption of 142 kWh/yr (WB, 2016), the projection would meet the consumption of 28 million individuals or 60% of the 2020 projected Niger Delta population.

The estimated energy from AD in this study is far higher than the total electricity from AD in the UK in 2014, which was 1.9 TWh (DEFRA, 2016) and also higher than the energy from biodegradable waste which was 1.95 TWh. Germany a leader in the renewable energy sector, attained 57 TWh of electricity from Bioenergy (Burger, 2016) which was far higher than that of the UK at 29 TWh (DECC, 2016). In the US energy from Biogenic Municipal Solid waste and other biomass provided 11 TWh of energy (Shahan, 2016) which is also higher than the energy output of this study. For the overall food waste generated, it was lower than that of the UK, where food and drink waste from households were 7 million tonnes (DEFRA, 2016).

4.4 Chapter Summary

This chapter presented the first set of results from the experiments of the study. The Specific Waste Index of the food samples ranged between 0.2 and 1.5 with an average value of 0.5. Corn had the highest waste content consisting of the cob and husk. The tubers and plantain had values between 0.3 and 0.5. The average total waste content of the nine foods was 29%. Corn had the highest at 59% while egusi had the lowest waste content at 18%. Some samples have high waste content with a low organic waste component, while some have low waste content with a high organic waste component.

The results of the food waste characterisation showed that the total solid content varied between 7 and 82% with an average value of 34%. Egusi shell and groundnut husk had the highest TS content while water hyacinth and ugwu stalk had the lowest values. For the tubers and plantain the TS values ranged between 15 and 37%. The VS/TS values ranged between 84% for water hyacinth to 97% for egusi shell and corn waste. Crude proteins ranged between 6% for egusi shell to 37% for ugwu stalk while crude fibre ranged from 7% for yam peel to 82% for egusi shell. Oil content was generally low for the group with only cassava peel having a high value of 25%. The Nitrogen Free Extracts was generally high in 80% of the samples, ranging from 82% for yam peels to 11% for egusi shell.

The Theoretical Bio-Methane Potential on a VS basis showed a narrow range of values from (540 - 619) x 10^3 m^3/kg VS with cassava peel having

the highest value and ugwu stalk with the lowest. The methane content varied between 51-58%. On a fresh weight basis, the biogas potential varied widely from 33 m^3/t FW for water hyacinth to 460 m^3/t FW for egusi shell. An analysis of the results showed that there is a perfect correlation between the biogas yields on a fresh weight basis and the individual TS and VS content.

The results of the regional waste quantification showed that the Niger Delta had a food waste potential of 2,600 – 4,100 (10^3 tonnes/yr) for eight of the commonly consumed foods. Corn had the highest contribution of waste at 590 -1200 (10^3 tonnes/yr) while egusi had the lowest at 62 - 120 (10^3 tonnes/yr). The total clean energy potential of the waste is 2.5 – 3.9 TWh/yr with corn waste contributing 31% to the mix and the tubers and plantain contributing 43%. This can potentially meet up to energy demand of 88% of the households in the Niger Delta or 60% of the projected 2020 Niger Delta population.

This section has estimated the regional waste productions from the Niger Delta based on food consumption patterns. The estimated bioenergy potential from the food waste was also presented. The results show that a high amount of clean energy can be produced from food wastes that would have otherwise gone to landfills and added to environmental degradation. The findings are a useful argument for the adoption of AD technology, which can contribute to keeping the environment clean and provide much needed energy for the Niger Delta. The next Chapter will present the results of the bioreactor designs and experimental bio-methane potential results.

Chapter 5 Results and Discussion: Bioreactor and Bio-Methane Potential Tests

The previous chapter presented the results of the waste and bioenergy potential of the Niger Delta. This chapter presents the results of the testing of various configurations of bioreactors. Next the results of the anaerobic co-digestion of the food waste from the four most common foods in the Niger Delta (yam, cassava, cocoyam and plantain) and Water Hyacinth are presented. These co-digestion results are then compared to the results from the mono digestion to determine the effect of water hyacinth on gas production.

5.1 Configuration tests

5.1.1 Results

The results of the bioreactor tests show that for the first configuration there was a 68% failure rate and out of those failures, 60% were caused by gas leaks. For the second and third configurations, they had 100% success rates. The results of the successes and failures of each bioreactor configuration test are presented in Table 5-1.

5.1.2 Discussion

Configuration 1

The first configuration had five components with three measuring units and one temperature control unit. There was no data logging capabilities. The system was meant to be used manually to measure biogas production using basic components. The reactor suffered problems with results showing a 68% failure rate. 60% of the failures were from gas leaks while the rest were from a combination of equipment failure and component constraints. The major limitation of the system came from the reactor lid. It did not always form an airtight cover for the vessel. Various methods were tested to make the lid airtight, including the use of PTFE tape, EPDM rubber rings and a combination of both. The results were mixed. The lid had four holes with customised inserts, which limited the number of components that could be added. The holes were improvised to receive more items using corks and silicon but there were still leaks. Another cause of failure for the system was the inoculum introduction. The method required for inoculum to be injected through a syringe. This was to be accomplished after the system had been heated and sealed. The narrowing of the syringe barrel led to particulates accumulating at the syringe's hub while being injected. This blocked the opening, preventing any further injection of inoculum. This led to a change of the experimental method for subsequent configurations; allowing the inoculum to be added at the beginning of the process before the reactor was sealed.

Defects of the system were mainly its inability to be gas tight and the inability of the system to accommodate more than four components.

Table 5–1 Results of Bioreactor Configuration tests performed in this study

Configuration 1		
Experiment	**Success/Failure**	**Comments**
1	Success	Minimum Components
2	Success	Minimum Components
3	Failure	Gas leak: No gas measured
4	Success	Minimum Components
5	Success	Minimum Components
6	Success	Minimum Components
7	Failure	Gas leak: No gas measured
8	Failure	Gas leak: Gas production suddenly stopped
9	Failure	Gas leak: Gas production suddenly stopped
10	Failure	More components added to reactor. Particles from digestate prevented the inoculum from being injected via syringe into reactor.
11	Failure	Particles from digestate prevented the inoculum from being injected via syringe into reactor.
12	Failure	Gas leak: No gas measured
13	Failure	Gas leak: No gas measured
14	Failure	Gas leak: No gas measured
15	Failure	Gas leak: No gas measured
16	Success	System working but gas bag failed to collect gas.
17	Failure	Flowmeter software error
18	Success	System working fine
19	Failure	Flowmeter software error
20	Failure	Temperature Controller error
21	Failure	Temperature Controller error
22	Failure	Gas leak: Gas production suddenly stopped
Configuration 2		
Experiment	**Success/Failure**	**Comments**
23	Success	All components working fine
24	Success	All components working fine
25	Success	All components working fine
26	Success	All components working fine
27	Success	All components working fine.
31	Success	All components working fine
Configuration 3		
Experiment	Success/Failure	Comments
28	Success	Multi-reactor system working fine
29	Success	Multi-reactor system working fine
30	Success	Multi-reactor system working fine
33	Success	Multi-reactor system working fine
34	Success	Multi-reactor system working fine
35	Success	Multi-reactor system working fine

Configuration 2

The second configuration had seven components with five measuring units of which three had data logging capabilities. Compared to the first configuration, a flow meter, pressure gauge and gas analyser were added. This configuration was successful with no gas leaks during the testing. The custom-made glass vessel came with a lid that had eight holes and gas tight inserts to securely hold integrated components. In addition it had a Fluorinated Ethylene Propylene (FEP) coated O-ring and a quick release clamp that held the lid in place and kept the system airtight. A pressure

gauge was also introduced into the configuration to verify the absence of gas leaks. Specialised components were introduced into the system. These included a digital mass flow meter, biogas analyser and pH meter, each having data logging capabilities. The main benefit of these additions was that once the experiment started, it could be allowed to run without any further human input. The gas analyser added a novel touch to the system by providing biogas data that was not available in literature. This data was the continuous analysis of biogas composition for the full duration of a BMP test. Researchers took few measurements of biogas composition and used those values to make generalisations on methane potentials of substrates.

Compared to the first system, there were no defects to this system. It is highly recommended as a cheaper alternative to the commercially available bioreactors that offer similar functions. Those reactors go for sale between £10,000 and £30,000 and are not affordable for laboratories in developing countries. Also the system basically runs itself and requires no human input once it is in operation. This is suitable for remote areas where there is limited technological expertise. It also eliminates constant human interaction with the system, which could cause system interruption or failure. There is also the possibility of adding an Internet connection to the system to give distant researchers access to real time data for instant analysis.

Configuration 3

The success of the second configuration, led to the creation of a third configuration. This was designed to provide a solution for simultaneous batch reactions. The BMP experiments to be performed with the bio-reactors were a comparative analysis between feedstock. In order to reduce the possibility of any variable changing between the AD tests, simultaneous testing of feedstock would need to be undertaken. Running the experiments consecutively could lead to changes in either the feedstock or inoculum. For the feedstock, physiological changes could occur over time. This includes degradation of samples from decomposition and disruption of cells if frozen which can affect the results of anaerobic digestion (VDI, 2006). Additionally fresh AD samples that are stored lose dry matter and produce more methane than their fresh counterparts (Herrmann et al., 2011). For the inoculum, the microbes could either decline or increase in population during the interval between BMP tests. This could be caused by lack of nutrients or changes in the environment of the inoculum. Furthermore running the tests simultaneously reduces the overall time taken to complete the experiments. It also eliminates the cost of buying individual bioreactor systems for each of the batches.

The third configuration had five components with two measuring units consisting of one data-logger. Compared to the previous configurations, the

heating and agitation were combined in the shaking water bath, while the pressure gauge and flow meter were removed. There were data logging capabilities for the gas analyser. The tests using this configuration were successful with no gas leaks or failures recorded. The reactors used were 500 ml airtight glass vessels. The lid was modified to accept additional components. The gas measuring system was switched back to the water displacement method used in Configuration 1. This was to eliminate the cost of purchasing nine additional flow meters. Similarly the expensive data logging pH meter was substituted for nine cheaper non data-logging models.

The main restriction to this configuration was the need for constant human interaction. This was required for taking biogas production measurements and noting of daily pH values. Furthermore the water bath had to be frequently topped up with water to replace evaporation water losses.

5.1.3 Cost and Energy Consumption

In this section the cost of building the bioreactors and the energy consumptions of the three configuration systems were analysed. The total cost of the first configuration was £968. The two most expensive components were the magnetic stirrer at £334 and the pH meter at £312. They both took 67% of the total cost. The total cost of the second configuration was £2,487 with the most expensive components being the digital mass flow meter and the custom-made reactor vessel. They both totalled 48% of the total cost. The total cost of the third configuration system was £2,462 with the most expensive components being the shaking water bath and the two gas analysers. They both took 80% of the costs.

The most expensive system was the 2nd configuration at £2,487. The high cost was a result of the advanced components of the system. The configuration utilised specialised measuring and analytic components that had data logging capabilities. Compared to the third configuration which could perform nine simultaneous tests, nine second configuration systems would cost £22,386. The cost of the multi-reactor system is nine times cheaper than using nine batch reactors. It is more economical to use the third configuration system if the Bio-methane Potential experiment requires multiple tests. This cheaper alternative would be at the expense of data-logging equipment that would eliminate the need for human input. Table 5-2 presents the various configurations and the breakdown of their costs.

The energy consumptions of the second and third configurations for the 20-day digestion period were determined using power meters. The first configuration was not considered because its high failure rate made it unsuitable for any BMP experiment. The second configuration consumed a total of 31 kWh. The bulk of that energy was consumed by the laptop connected with the biogas analyser which consumed 64% of the total

energy. The 3rd configuration system consumed 74 kWh. The bulk of that was consumed by the shaking water bath at 73%.

Table 5–2 Cost of components of three bio-reactors in this study

Configuration 1		
Component	**Cost (£)**	**Brand**
Reactor Vessel and Lid	113.2	Sigmaaldrich
Heating System	192.6	Omega
Magnetic Stirrer and rod	344.6	Cole Parmer
pH Meter	312.0	Oakton
Gas measurement system	5.6	Generic
Total	**968.0**	
Configuration 2		
Component	**Cost (£)**	**Brand**
Reactor Vessel and Lid	572.4	AM Glassware
Heating System	156.3	Omega
Magnetic Stirrer and rod	344.6	Cole Parmer
pH meter with datalog	241.2	Omega
Flowmeter	625.0	Aalborg
Biogas Analyser	382.8	Dynament
Pressure Gauge	15.0	Generic
Laptop	150.0	IBM
Total	**2,487.3**	
Configuration 3		
Component	**Cost (£)**	**Brand**
9 Reactor Vessels and Lids	20.1	Simex
Shaking Water bath	1200.0	Grant Instruments
pH meter and 9 electrodes	305.4	Hanna
Gas measurement system	20.4	Generic
2 Biogas analyser	765.6	Dynament
Laptop	150.0	IBM
Total	**2,461.5**	

The third configuration consumed more than twice the amount of energy consumed by the second configuration. When comparing the third configuration system with nine second configuration systems, the third configuration system would consume 3.7 times less energy than the nine systems. Hence it is more energy efficient to use the multi-reactor system. The results are presented in Table 5-3.

The biogas analyser used in these configurations used the Non-Dispersive Infra Red (NDIR) technology to detect the biogas constituents. The output from the sensor has been shown to be comparable to the results from conventional gas measurement technologies. A study on such sensors by Jun et al. (2011) showed that the accuracy of such sensors was very high when compared to measurements from conventional systems. Yasuda et al. (2012) showed that when measuring CO_2, NDIR systems produced results that were similar to the highly accurate LI6262 CO_2 analyser. NDIR technology was shown by Stephens et al. (1996). to be accurate for measuring alkane compounds which include methane, but were poor for measuring aromatic compounds. The NDIR biogas analyser is a cheaper and light weight alternative to the Gas Chromatograph and other expensive

gas analysers and is appropriate for use in BMP tests. Laboratories in developing countries that do not have access to Gas Chromatographs or the NDIR analyser can use the Liquid Displacement Method (LDM) to measure the methane content of biogas. A study by Pham et al. (2012) showed that there is not much difference between using a GC and the LDM in measuring methane content of biogas.

Table 5–3 Reactor Configurations and Energy Consumption for this study

Configuration 2	
Equipment	**Energy Consumption 20 days (kWh)**
Reactor Vessel	None
Heating System	7.4
Magnetic Stirrer	2.9
pH meter	0.2
Flow meter	0.5
Laptop with gas analyser	19.7
Pressure Gauge	None
Total	**30.7**
Configuration 3	
Equipment	**Energy Consumption 20 days (kWh)**
Reactor Vessel	None
Heating system and agitator	54.5
pH meter	Battery
Gas measurement	None
Laptop with gas analyser	19.7
Total	**74.2**

5.2 Biogas Production of Food Waste Co-Digested with Water Hyacinth

This section presents the results of the anaerobic co-digestion of the food waste from the four most common foods in the Niger Delta (yam, cassava, cocoyam and plantain peels) and Water Hyacinth. The results are further analysed using the Modified Gompertz kinetic model (Zwietering et al., 1990). The Methane and Carbon Dioxide content of biogas over the 20-day retention period is also presented. Propane and other flammable gases were ignored because it is assumed that the dominant gas in biogas is Methane.

5.2.1 Biogas Yields

The results from the BMP tests showed that YP+WH had the highest biogas yield at 0.42 m^3/kg VS. Next were CoP+WH and PP+WH at 0.39 m^3/kg VS and 0.38 m^3/kg VS respectively. CP+WH had the lowest yield at 0.29 m^3/kg VS. The low yield of the CP+WH was expected because studies had shown that the cyanide content of the cassava peels was detrimental to the AD microbes especially the methanogens (Cuzin et al., 1992; Cuzin and Labat, 1992; Ubalua, 2007). The biogas yields of the various co-substrates provided the baseline for a comparative analysis of their biogas potentials. The results are presented in Table 5-4. The biogas yields had relative errors of less than 4% indicating high precision. Figure 5-1 presents their Specific Biogas Yields

(SBY) which is the cumulative biogas production after the contribution of the inoculum has been removed.

The biogas yields place the samples into the category of vegetable waste, potato waste, food waste, fruit waste, slaughterhouse waste and household waste as reported by Deublein and Steinhauser (2011). Energy crops such as maize, wheat, sugar beet and straw have biogas yields of 560, 610, 381 and 324 m^3/tonne respectively. Tubers like potatoes have biogas yields of 276 to 400 m^3/tonne. The sample with the closest biogas production to the co-digested substrates is grass with yields of 298 to 467 m^3/tonne (NNFCC, 2016). Additionally the VS/TS analysis of the samples were within the range of VS/TS for plant waste as reported by Al Seadi et al. (2013) and higher than the 70-80% for energy crops as reported by Neureiter (2013). Furthermore common biodegradable organic matter should have a VS/TS of 70% and above while feedstock with lower than 60% VS/TS are not suitable as substrates for the AD process (Steffen et al., 1998). These combined factors make the food wastes suitable feedstock for the AD process.

The biogas from the AD process may be combusted in gas turbines to provide electricity that would power households at the community levels. The biogas could also be used as biofuel for a Combined Heat and Power (CHP) system. Using a CHP unit, the energy system would provide electricity for households and heating for various purposes including cooking, boiling water and drying/preserving locally grown crops. The biogas could also be directly combusted in biogas stoves for cooking purposes.

Table 5–4 Characteristics and Biogas Yield of Co-Digested Feedstock (means ± relative error) S:I=1:2

	YP+WH	CP+WH	CoP+WH	PP+WH	Inoculum
TS (g)	9.5	9.4	9.5	9.4	27.0
VS (g)	8.4	8.4	8.4	8.4	16.8
CrP %VS	13.1	12.4	13.1	12.4	-
CrF %VS	11.3	12.1	11.3	12.1	-
Oils %VS	2.4	18.1	2.4	18.1	-
NFE %VS	73.2	57.4	73.2	57.4	-
Ash (g)	1.2	1.1	1.2	1.1	-
FW: WH ratio	2:1	2:1	2:1	2:1	-
M (10^{-3} m^3/kg VS)	469.0±0.9	356.0 ± 13.1	445.0±9.3	440.0 ± 14.9	-
SBY (10^{-3} m^3/kg VS)	419.0±0.9	285.0 ± 13.1	388.0±9.3	383.0 ± 14.9	-
Effluent pH	7.8±0.0	7.8 ± 0.0	7.9±0.0	7.9 ± 0.0	-

The daily and cumulative biogas production curves for the samples are presented in Figures 5-2 and 5-3. The results of the daily gas production show that biogas production peaked within the first three days for all the samples. The peak gas production for the YP+WH, CoP+WH and PP+WH were on the second day, while for the CP+WH it was on the third day. This implied a rapid consumption of the readily available nutrients by the microorganisms and subsequent rapid conversion of the intermediate

products. By the fourth day, gas production was in the retardation phase going by Monod's Kinetic Model (Monod, 1949).

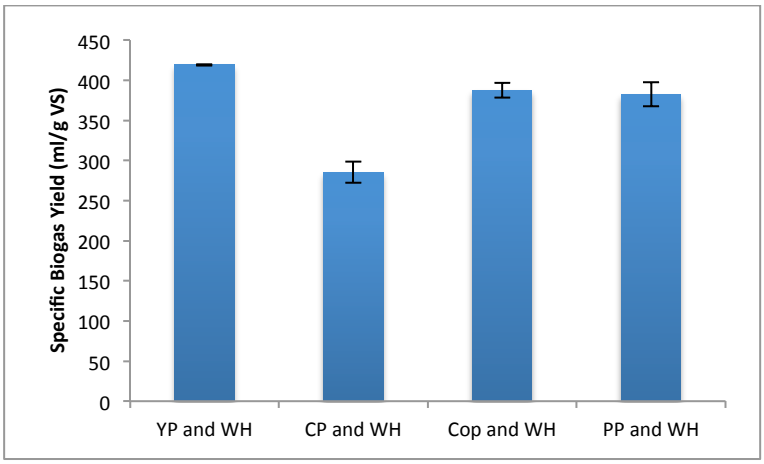


Figure 5–1 Specific Biogas Yields of Co-Digested Feedstock (Error bars indicating relative error of measurements)

Most of the biogas yields were obtained within the first six days, with YP+WH, CP+WH, CoP+WH and PP+WH producing 80%, 70%, 75% and 71% of their total production by the sixth day.

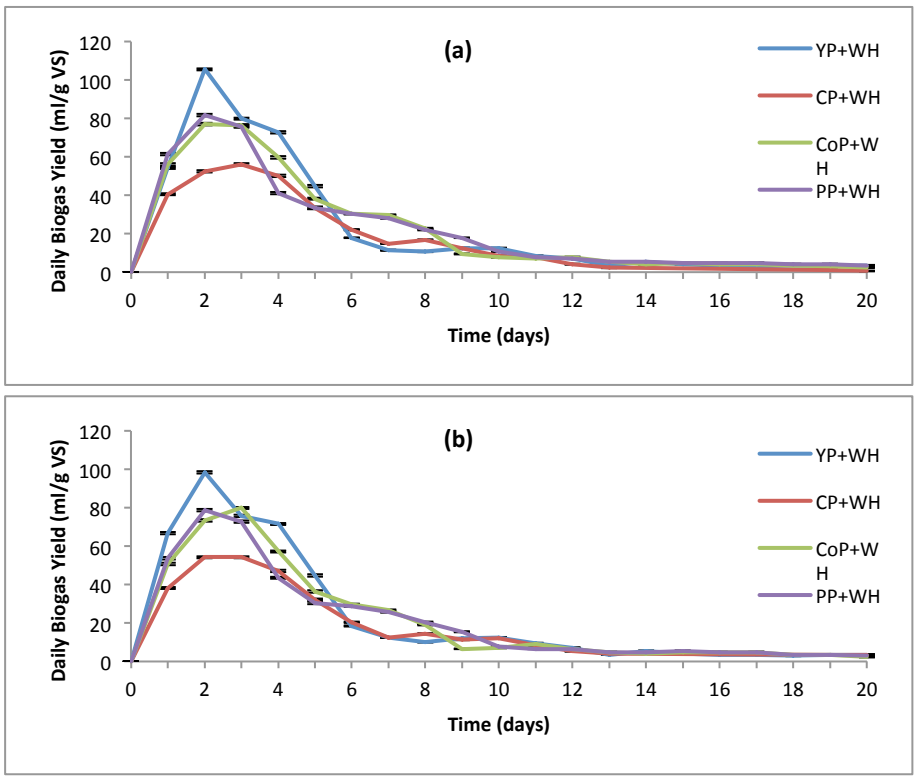


Figure 5–2 Results from duplicate test of daily biogas yields of Co-digested Feedstock (a) Test 1 (b) Test 2

Figure 5-3 presents the graph of the cumulative biogas production of the samples. The curves are similar to biogas production curves in literature.

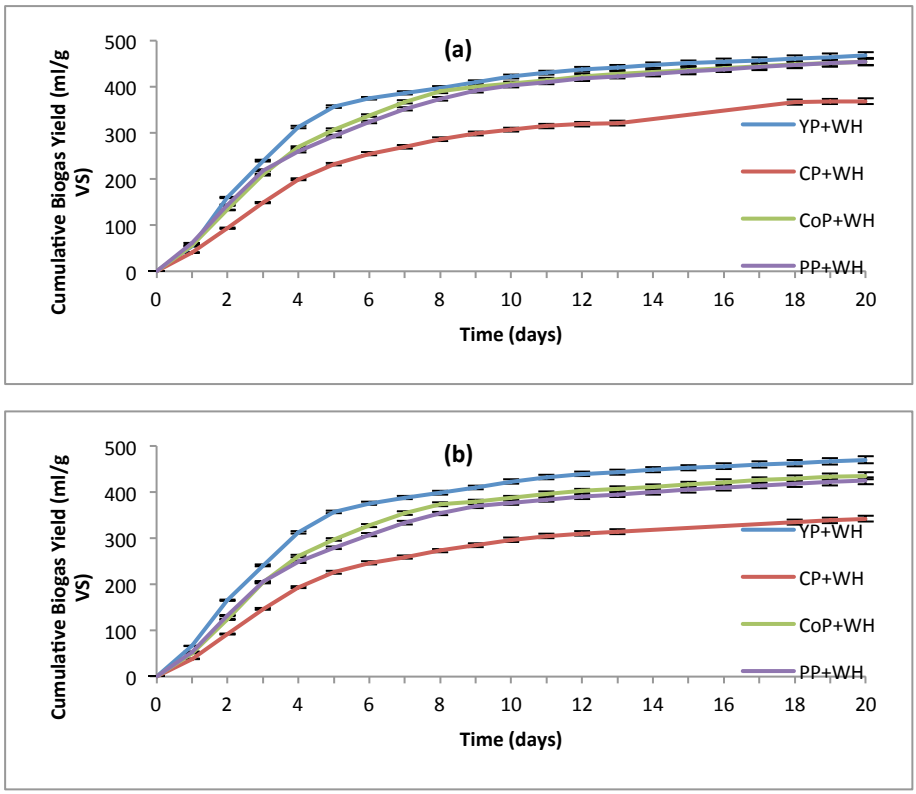


Figure 5–3 Results from duplicate test of cumulative biogas yield of Co-Digested Feedstock (a) Test 1 and (b) Test 2

5.2.2 Biodegradability

The nutrient composition of each co-substrate was used to calculate their theoretical biogas potential using the Baserga model. The model assumes that all nutrients are converted to biogas. The theoretical and measured yields were used to calculate the Biodegradability (BD) of the substrate which is the percentage of the theoretical to the measured biogas yields (Triolo et al., 2011; Triolo et al., 2012). YP+WH had the highest biodegradability at 76%. Next were CoP+WH and PP+WH which had values of 70% and 69% respectively. Least biodegradable was CP+WH, which had a very low value of 48%. The results are presented in Table 5-5.

Table 5–5 Theoretical and Experimental BMP of Co-Digestion

Food Waste	Measured Biogas Potential (10^{-3} m^3/kg VS)	Theoretical Biogas Potential (10^{-3} m^3/kg VS)	Biodegradability (%)
YP+WH	419	551	76
CP+WH	285	596	48
CoP+WH	388	552	70
PP+WH	383	558	69

The variation between theoretical and actual values is occasioned by the presence of complex nutrients as found in plant based feedstock (Tambone et al., 2009) and the inability of microbes to access them. Other reasons are the consumption of nutrients by microbes for their growth (Kalyuzhnyi, 1997) and inhibitory factors. Drosg et al. (2013) stated that plant based feedstock attained 50-70% of their theoretical values when anaerobically digested. The results show that YP+WH, PP+WH and CoP+WH were either within or surpassed the range while the biodegradability of CP+WH was below the limit.

Despite CP+WH having the highest theoretical value of biogas production, the actual digestion produced a very low amount of biogas. This is caused by the cyanide content of the cassava peel that adversely affects the AD microbes (Cuzin et al., 1992; Ubalua, 2007). A method was developed by Cuzin and Labat (1992) to reduce the cyanide levels during the AD of cassava peels to a non-inhibitory concentration. The method utilised cyanide detoxification enzymes in a plug flow digester to reduce the cyanide concentration. Cumbana et al., (2007) and Bradbury (2006) used a “Wetting Method” to also reduce the cyanide content of the plant. The process involved mixing the cassava with water and spreading it out to dry in a thin layer. Bradbury’s method reduced the cyanide content by three fold over a five-hour period. Eventually Bradbury and Denton (2010) modified that method and lowered the time taken to reduce the cyanide content by the same factor to two hours. This was accomplished by drying the mixture in the sun rather than the shade. Such methods could improve the gas production from AD digestion and co-digestion of cassava peels.

The difference between the measured biogas and the theoretical yield may be reduced by chemical pre-treatment of the substrates. This would break down the lignin and other complex molecules into shorter chains that can be readily consumed by the microbes. Studies by Patil et al. (2011), Cheng et al. (2010), Gao et al. (2013) and Cheng et al. (2013) showed that using chemicals to pre-treat water hyacinth reduced lignin and broke down crystalline cellulose. In each of the studies, biogas production increased after pre-treatment. In order to reduce the gap between measured and theoretical values of the samples, chemical pre-treatment and reduction of inhibiting substances from the feedstock need to be implemented.

5.2.3 pH Values

The pH values of the BMP tests over the 20-day period varied between 7 and 8. In all tests the pH values fell within the first two days indicating the presence of organic acids. The lowest pH was obtained from the YP+WH on the second day. This is most likely a result of the rapid conversion of high amounts of NFEs into VFAs. The pH of the CP+WH did not drop as low as the other samples. The reason was probably the inhibition from the cyanide

preventing the microbes from converting the nutrients into VFAs. After the second day, there was a steady increase in pH values, and from the eight day, the values remained steady. The final pH values for the samples were between 7.8 and 7.9, indicating that there was no accumulation of excess organic acids. This implied that the substrate to inoculum ratio of 1:2 was sufficient enough to provide a buffer to prevent any acid build up.

5.2.4 Model Kinetics

This section presents the results of the model kinetics for the BMP of each substrate. The cumulative biogas production curves were fitted to the Modified Gompertz Model using non-linear regression and the kinetic constants were obtained. The Modified Gompertz Model gives the cumulative biogas production from batch digesters, assuming that biogas production is a function of bacterial growth. The model simulation was performed using Solver in Microsoft Excel, which utilised the Generalised Reduced Gradient (GRG) non-linear algorithm. The results from the simulation are presented in Table 5-6.

The lag phase, which is the minimum time required for the microorganisms to adapt to the environment and commence gas production was less than five hours in all tests. This is because the inoculum had been acclimatised to the bioreactor environment for a week before the BMP test. The process degassed the microbes and created a hunger phase. This led to an almost immediate consumption of the introduced substrate. The microbial activity led to instant gas productions thereby reducing the lag phase.

Table 5–6 Kinetic Parameters and Simulated Biogas Yields of Co-Digested Feedstock (means ± relative error)

	YP+WH	CP+WH	CoP+WH	PP+WH
Lag Phase, λ (days)	0.2 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.00 ± 0.0
Rm (10^{-3} m^3/kg VS/day)	82.4±1.4	45.6 ± 0.1	66.7±0.4	61.5±1.4
P (10^{-3} m^3/kg VS)	444.0±1.3	337.0 ± 11.2	427.0 ±10.4	421.0 ±14.4
T80 (days)	6.0 ± 0.0	8.4 ± 0.3	6.8±0.0	7.4±0.1
R^2 (%)	92.9	94.4	94.8	95.9
R^2 Adj. (%)	90.5	92.6	93.0	94.5
RMSE	0.2	0.1	0.1	0.1
Biogas Production Measured (10^{-3} m^3/kg VS)	469.0 ± 0.9	356.0 ± 13.1	445.0 ± 9.3	440.0 ± 14.4
Biogas Production Simulated (10^{-3} m^3/kg VS)	444.0 ± 1.3	336.0 ± 11.0	427.0 ±10.4	420.0 ± 14.4
% Difference	5.5 ± 0.1	5.5 ± 0.4	4.1±0.3	4.5±0.0

The T80 or Technical Digestion Time is the time needed to produce 80% of the total gas production (Palmowski and Muller, 2000). For the various substrates, YP+WH had the shortest T80 period of 6 days. This indicates a rapid consumption and conversion of available nutrients. The longest T80 was for the CP+WH at 8.4 days. This could have resulted from the toxic effect of cyanide on the microbes. The result would be a reduction in the microbial population causing the remaining microbes to take longer periods

to consume the available nutrients. The T80 values for the CoP+WH and PP+WH were 6.8 days and 7.4 days respectively. The T80 period can be used as a benchmark for the retention period or Hydraulic Retention Time of an AD process.

The measured and simulated biogas values are presented in Figure 5-4. In all results, the measured biogas was more than the simulated values. The respective simulated biogas values of YP+WH, CP+WH, CoP+WH and PP+WH were 95%, 95% 96%, 96% of their measured values. Figure 5-5 shows the curves of the measured and simulated biogas production. The curves have a very close fit indicating that the measured biogas yields are in agreement with the simulated values. This is confirmed by the high values of R^2 of 0.9 for all samples. The conclusion is that these results can be used to validate the Modified Gompertz Model.

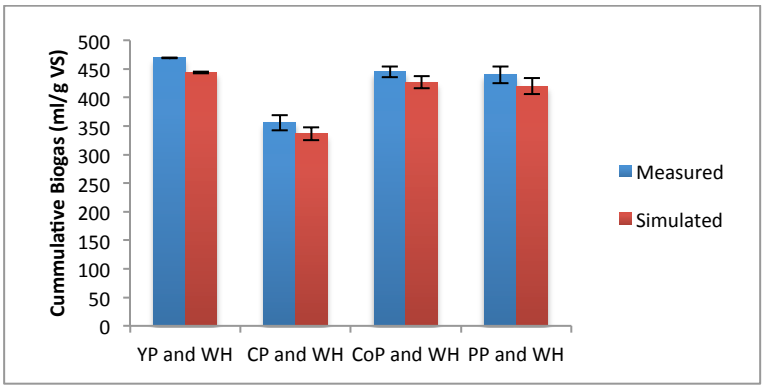


Figure 5–4 Measured and Simulated biogas yields of Co-Digested Feedstock based on Modified Gompertz Model (Error bars indicating relative error of measurements)

5.2.5 Sensitivity Analysis of Modified Gompertz Model

A one-at-a-time sensitivity analysis was performed to determine which of the kinetic constants of P, Rm, and λ of the Modified Gompertz Equation had the most effect on the model output. The method involved modifying a single kinetic constant, while leaving the other constants at their nominal values and subsequently observing the effect on the output. The process is repeated for each kinetic constant. For this analysis, the nominal values were taken from the biogas yield simulation of YP+WH, Test 1. They were: P = 442, Rm = 84 and λ = 0.2. The analysis was performed using the What-If functionality of Microsoft Excel and the values ranged from -95% to +95% of the nominal values in increments of 5%. The results show that the variable that has the most impact on the output of the model is the Biogas Production Potential, *P*. The maximum biogas production rate, *Rm*, impacts on the output from 5% to 50% of its nominal value. After that there is almost no impact on the output. The lag phase, *λ*, has almost no effect on the output of the model from its lowest to highest values. *P* is the most important factor for

the implementation of the model. The results are plotted in a radar chart and presented in Figure 5-6.

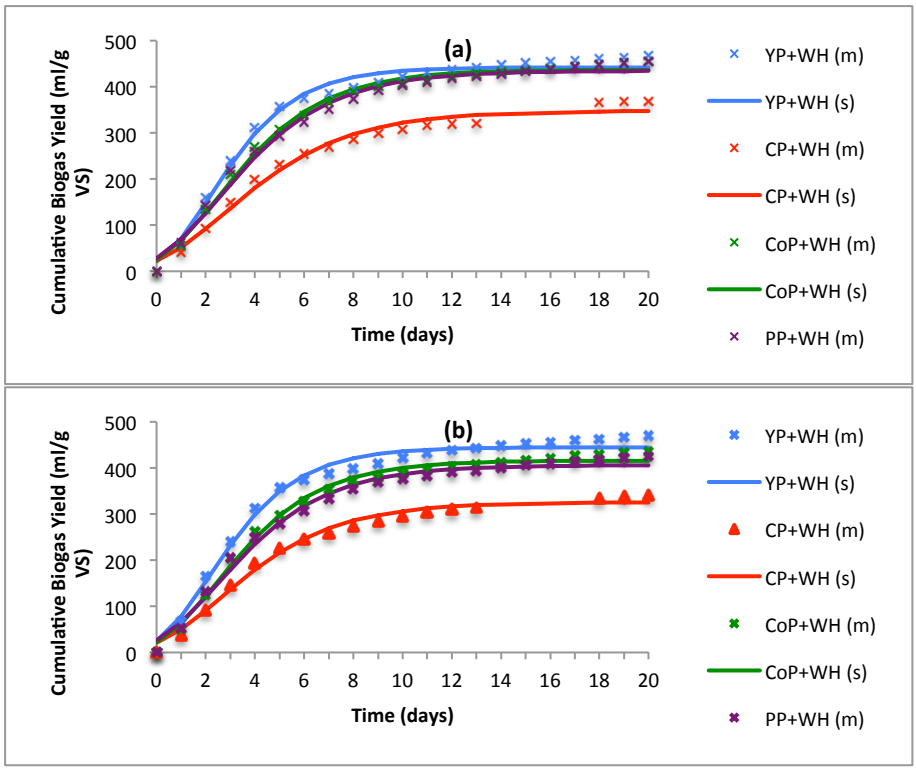


Figure 5–5 Results of duplicate test of Measured vs Simulated Biogas Yields of Co-digested Food waste (a) Test 1 (b) Test 2

(m) = measured, (s) = simulated

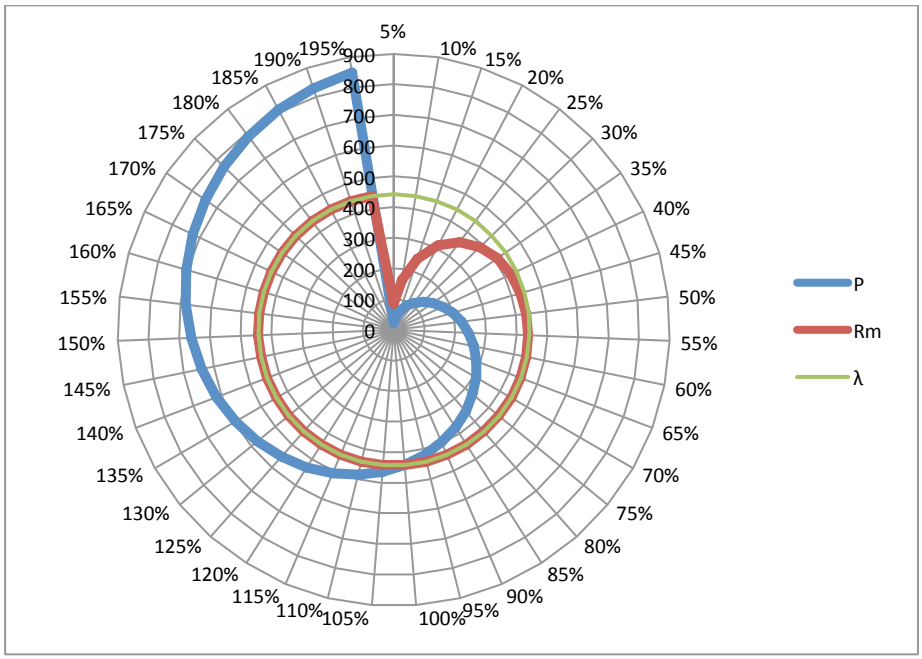


Figure 5–6 Sensitivity Analysis of the independent variables of the Modified Gompertz Model

5.2.6 Biogas Composition

This section presents the varying composition of the biogas produced during the 20-day retention time of the tests. The methane and carbon dioxide content were automatically analysed by an inline Non-Dispersive Infra Red (NDIR) biogas sensor. The propane content was also measured but the sensor had a saturation point at 5% wt of propane in the biogas. Hence it mainly indicated the presence of the hydrocarbon in addition to the Methane, Carbon Dioxide and other gases present. The sampling period was every 15 minutes and the results are presented in Figure 5-7. The sensor outputs show noise in the results, which may be attributed to the varying water vapour content in the biogas. Water vapour is reported to cause interference in NDIR sensors which may be reduced by drying the biogas before passing it through the sensor. This reduces the noise in the sensor output. To reduce the visual impact of the noise in the data, the moving average daily values were calculated and plotted in Figure 5-8. For all the samples, the initial biogas production consisted mainly of carbon dioxide with a lower amount of methane. The switch from a higher carbon dioxide content to a higher methane content occurred on the second day for CoP+WH and PP+WH and on the third day for both YP+WH and CP+WH. The highest average daily methane concentrations for YP+WH, CP+WH, CoP+WH and PP+WH were 37, 24, 38 and 40% respectively. The CoP+WH was the first to attain its maximum methane concentration by the third day, while the remaining three samples each attained their maximum values on the fourth day. As explained previously, the very low methane content in the CP+WH is a result of the cyanide content which is toxic to microbes especially the methanogens (Cuzin et al., 1992; Cuzin and Labat, 1992; Ubalua, 2007). The variation in the biogas composition support the understanding that methane and carbon dioxide content of biogas varies widely between the beginning, middle and end of a BMP batch test. The implication is that a single gas analysis test is not sufficient to determine the methane content of the biogas yield of a feedstock. There needs to be multiple sample points in order to determine the true methane potential of a substrate. The average methane content of the whole duration of the experiment would give a false methane potential result because it would include the very low residual methane content at the end of the test. It is more practical to determine the average value for specific time frames. From the biogas yield results, the T80 period corresponds to the peak biogas yields. Consequently the average methane content was calculated for the T80 period, the remaining retention time (t-T80 days) and the whole duration of the test (t days). The results show that the average methane content during the T80 period is far higher than the other two periods measured. The results are presented in Table 5-7.

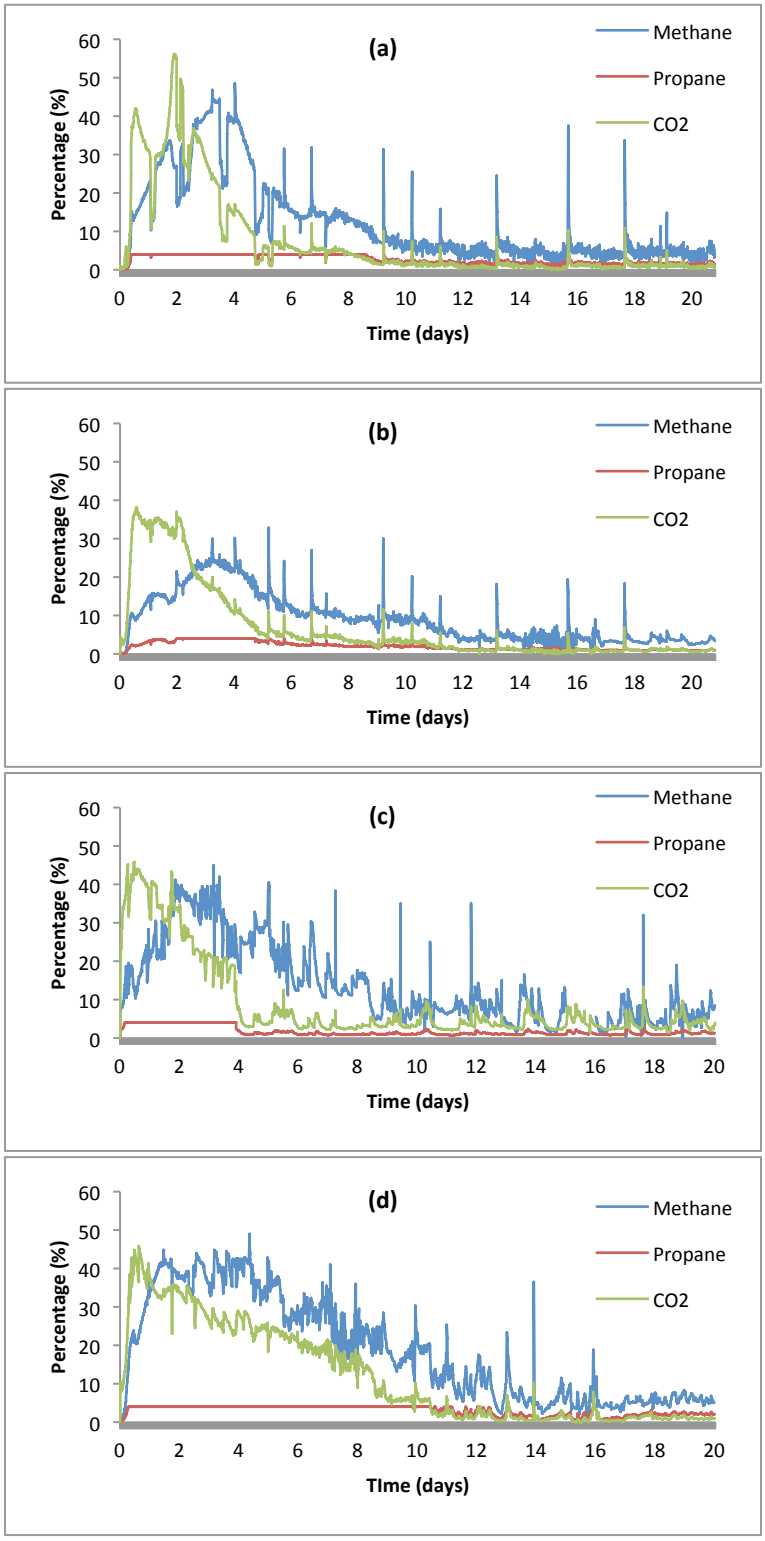


Figure 5–7 Biogas Composition every 15 minutes of (a) YP+WH, (b) CP+WH, (c) CoP+WH and (d) PP+WH

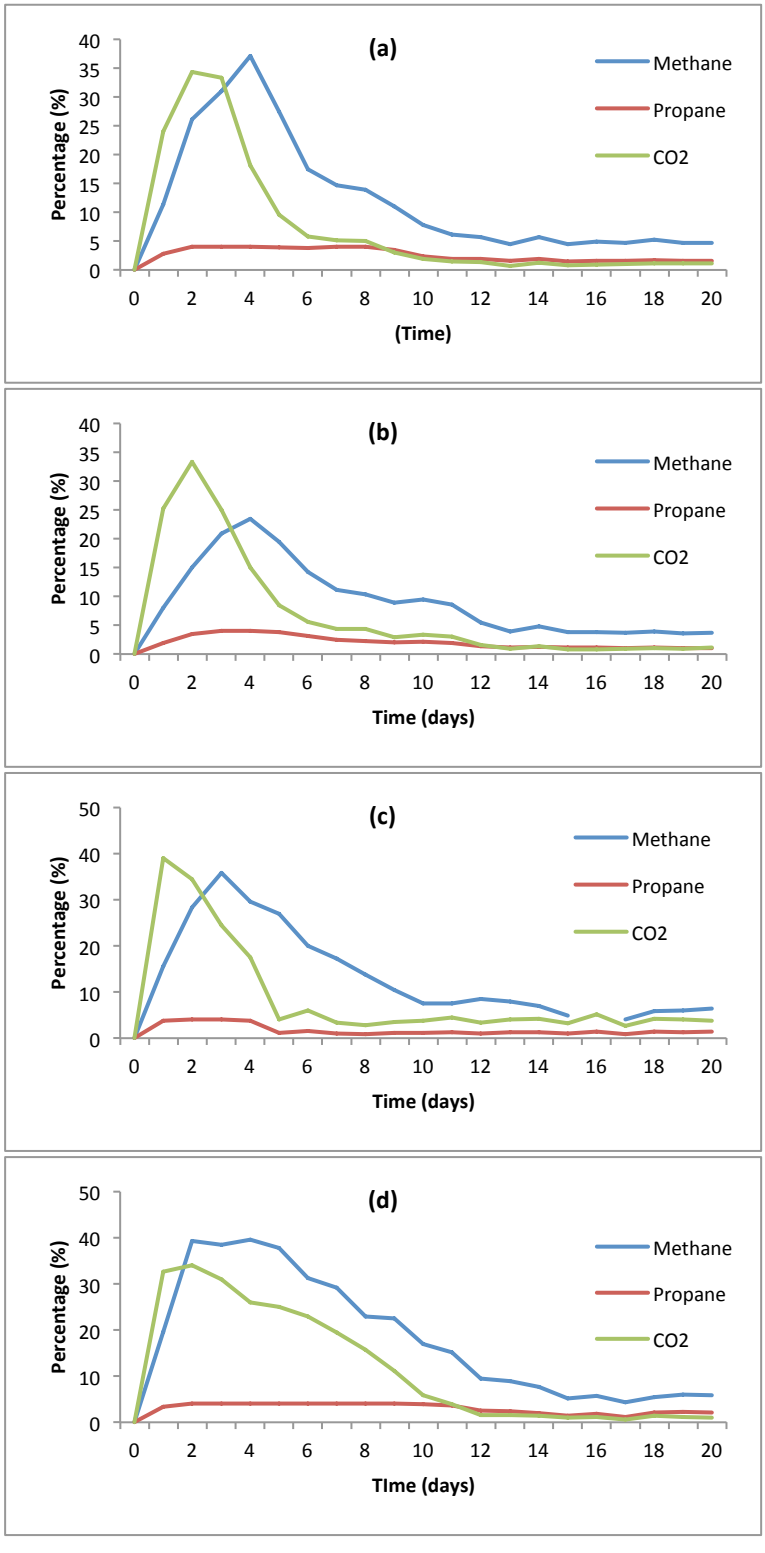


Figure 5–8 Moving Average Daily Biogas Composition of (a) YP+WH, (b) CP+WH, (c) CoP+WH and (d) PP+WH

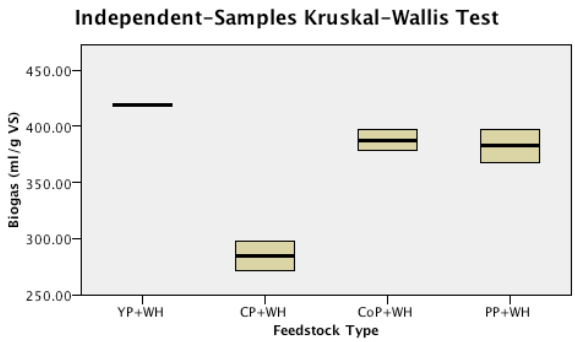
Table 5–7 Average Methane content over various stages of retention time for Co-Digested Substrates

Sample	T80 period (days)	% CH_4 T80 period (%)	% CH_4 t-T80 (%)	% CH_4 t (%)
YP+WH	6.0	25	7	12
CP+WH	8.4	15	5	9
CoP+WH	6.8	25	8	14
PP+WH	7.4	33	10	19

For all the samples, the average methane content for the T80 period was approximately three times the average content for the rest of the retention period (t-T80) and approximately twice the average content for the whole digestion period (t). This leads to a conclusion that it is necessary to take multiple gas samples for the biogas analysis during the AD process. It is also necessary to focus on the samples taken during the T80 period.

5.2.7 Statistical Analysis

Due to the small sample size (n=2) of the groups, the distribution of the data cannot be verified to be normal. Hence a non-parametric Kruskal-Wallis test was performed on the results to determine if there was any significant difference between the samples. The results showed that there was no significant difference ($p<0.05$) between the groups. The results are shown in Figure 5-9 and test statistics in Appendix 10.



Total N	8
Test Statistic	6.114
Degrees of Freedom	3
Asymptotic Sig. (2-sided test)	.106

1. The test statistic is adjusted for ties.
2. Multiple comparisons are not performed because the overall test does not show significant differences across samples.

Figure 5–9 Kruskal-Wallis Analysis of Co-Digestion Results

5.2.8 Efficiency of Bio-Reactor System

The efficiency of the bioreactor system was determined using the energy consumption of the system as presented in Section 5.1.3 and compared to the biogas production from each substrate using the efficiency equation presented below:

$$Efficiency\ (\eta) = \frac{Energy\ Output}{Energy\ Input} \times 100\% \ = \ \frac{Useful\ Energy\ Produced}{Energy\ Consumed\ by\ the\ System} \times 100\% \qquad (9)$$

The energy consumed by the bioreactor system over the 20-day retention period was 74 kWh (Table 5-3).

The useful energy produced was calculated for each substrate combination with the following assumptions:

I. For each feedstock combination, the nine reactor vessels contain the exact same substrate in the exact same quantity.
II. Each of the nine reactors produces the exact same amount of biogas (means of biogas production for each substrate used as the working value).
III. 60% of biogas is methane (approximate value of methane content in a an AD digester).

The Useful Energy Produced was determined by obtaining the methane content of the biogas and calculating its energy value in kWh using the Gross Calorific Value of Methane = 38 MJ/m^3 and the conversion of 1 MJ = 0.3 kWh. The results show that the efficiencies of the systems are less than one. This is a result of the low economy of scale of the system and high amounts of energy losses from the water bath. The results are presented in Table 5-8.

Table 5–8 Efficiency of bioreactor system using co-digested feedstock as substrate

	Biogas (10^{-6} m^3)	Methane (10^{-6} m^3)	Energy Output (kWh)	Efficiency (%)
YP+WH	3.5	2.1	0.2	0.3
CP+WH	2.4	1.4	0.1	0.2
CoP+WH	3.3	1.9	0.2	0.3
PP+WH	3.2	1.9	0.2	0.3

Energy is lost in the form of evaporation, radiation and through the tank walls. To estimate the heat loss, Q, from an open tank, equation (10) is used.

$$Q = Q_{evaporation} + Q_{radiation} + Q_{transmission\ through\ walls} \qquad (10)$$

The full set of calculations for the heat loss of the system are shown in Appendix 3. The heat loss was calculated to be 37 kWh and is noteworthy when addressing the inefficiency of the system, considering the fact that the shaking water bath consumes most of the power of the system. The system

is not efficient in producing any practical energy. The system is only useful as a BMP test kit.

5.3 Biogas Production of Food Waste

This section presents the results of the biogas production and kinetic modelling of the mono-digested food waste. The results are then compared to the co-digestion values to determine the effect of water hyacinth on biogas yields.

5.3.1 Biogas Yields

The biogas production results of the four food wastes followed the same ranking as the co-digested samples. YP produced the highest Specific Biogas Yield of 0.55 m^3/kg VS. Next were CoP and PP at 0.41 m^3/kg VS. The least yield was from CP at 0.37 m^3/kg VS. As explained in Section 5.2, the low biogas yield for the CP was likely a result of the toxic effect of cyanide on microbes, leading to AD inhibition (Cuzin et al., 1992; Cuzin and Labat, 1992; Ubalua, 2007). From the results, the mono-digested substrates are ranked in the same order of highest to lowest as their co-digested counterparts in terms of biogas production. The results of the mono-digestion tests are presented in Table 5-9 while the Specific Biogas Yields are presented in Figure 5-10. The biogas yields had relative errors of less than 3% indicating high precision.

Table 5–9 Characteristics and Biogas Yield of Mono-Digested Feedstock (means ± relative error) S:I = 1:2

	YP	CP	CoP	PP	Inoculum
TS (g)	9.1	8.9	9.2	8.9	27.0
VS (g)	8.4	8.4	8.4	8.4	16.8
CrP %VS	9.6	8.6	9.6	8.6	13.8
CrF %VS	7.0	8.2	7.0	8.2	1.9
Oils %VS	1.2	24.6	1.2	24.6	1.1
NFE %VS	82.2	58.6	82.2	58.6	-
Ash (g)	0.7	0.5	0.7	0.5	10.3
FW: WH ratio	3:0	3:0	3:0	3:0	-
M (10^{-3} m^3/kg VS)	621.0 ± 20.6	437.0 ± 5.4	472.0 ± 7.5	470.0 ± 7.8	-
SBY (10^{-3} m^3/kg VS)	551.0 ± 20.6	367.0 ± 5.4	414.0 ± 7.5	412.0 ± 7.8	-
Effluent pH	7.8±0.0	7.1 ± 0.1	7.9 ± 0 .0	7.9 ± 0.0	-

The results of similar comparative AD tests for exotic food waste aligned with the biogas yields of this study. The results from Ojikutu and Osokoya (2014) showed that yam peel digested with cow dung produced more biogas than plantain peel and cow dung. This was supported by Makinde and Odokuma (2015) who co-digested yam and plantain peels, each in various ratios with cow dung. The yam peels produced more biogas than the plantain peels in all tests. Similarly, Igwe (2014) showed that plantain peels produced more biogas than cassava peels. The findings of this study confirm the results in literature.

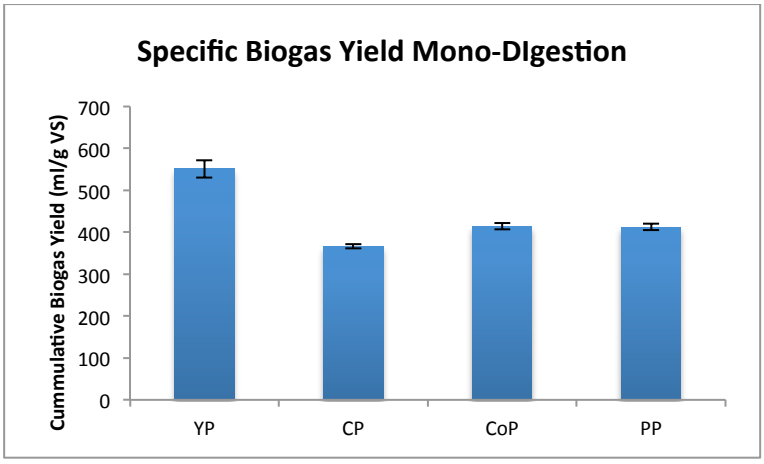


Figure 5–10 Specific Biogas Yields of Mono-Digested Feedstock (Error bars indicating relative error of measurements)

5.3.2 Biodegradability

The biodegradability (Triolo et al., 2011; Triolo et al., 2012) of each substrate was calculated using the theoretical biogas potential and the measured values. YP had the highest biodegradability at 100%. Next were CoP and PP at 75% and 73% respectively. The lowest was CP at 59%. The results are presented in Table 5-10.

Table 5–10 Theoretical and Experimental BMP of Mono-Digested Food Waste

Food Waste	Experimental Biogas Potential (10^{-3} m^3/kg VS)	Theoretical Biogas Potential (10^{-3} m^3/kg VS)	Biodegradability (%)
YP	551	549	100
CP	367	619	59
CoP	414	552	75
PP	412	562	73

The high biodegradability of YP suggests that there was some synergetic activity in the digester that helped to improve the biogas yield beyond its theoretical values. The high biodegradability is supported by the YP having very high amounts of NFEs at 82%. The NFEs are soluble carbohydrates, which are easily consumed by microbes. The low biodegradability of CP results from the presence of cyanide, which adversely affects AD microbes. The toxins most likely led to an inefficient consumption of the available nutrients due to incapacitated microbes. This would explain the large variation between the measured and theoretical values, since the theoretical values are based on complete nutrient conversion. The biogas productions of the mono-digested food waste were closer in value to their theoretical values than the co-digested samples.

The daily and cumulative biogas production curves are shown in Figure 5-11 and 5-12 and show little variations between the replicates. Gas production for the YP, CP and PP peaked on the second day while for CoP it was on the third and fourth day for each replicate.

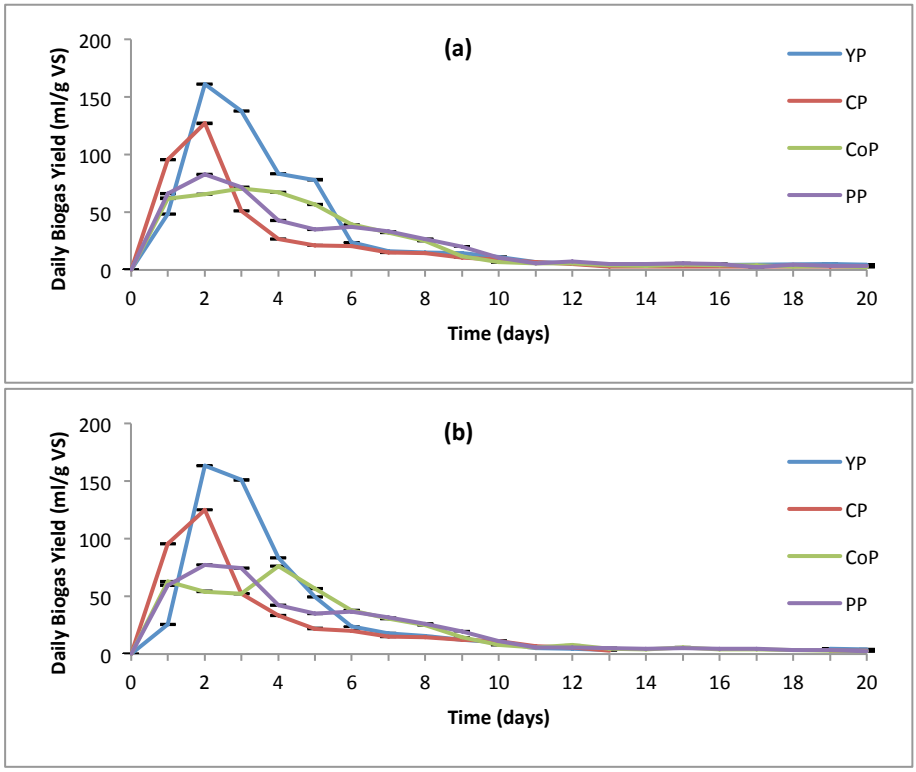


Figure 5–11 Results from duplicate test of daily Biogas Yields of Food Waste (a) Test 1 and (b) Test 2

Similar to the gas production profile of the co-digested substrates, by a quarter of the retention time, most of the gas had been produced by the samples. The percentage of biogas produced by the sixth day for YP, CP, CoP and PP were 83%, 79%, 75% and 71% respectively. It was an improvement for the CP, whose co-digested counterpart produced 70% of the total biogas by the same period. The YP also improved from the 80% of its co-digested counterpart. For the CoP and PP the values were unchanged. Biogas production peaked on the second day for YP, CP and PP while for the CoP it was on the third and fourth day for each replicate. This was an improvement for the CP whose co-digested counterpart had a peak gas production on the third day. The final pH values for the samples were between 7.1 to 7.9, with CP having the lowest final pH value.

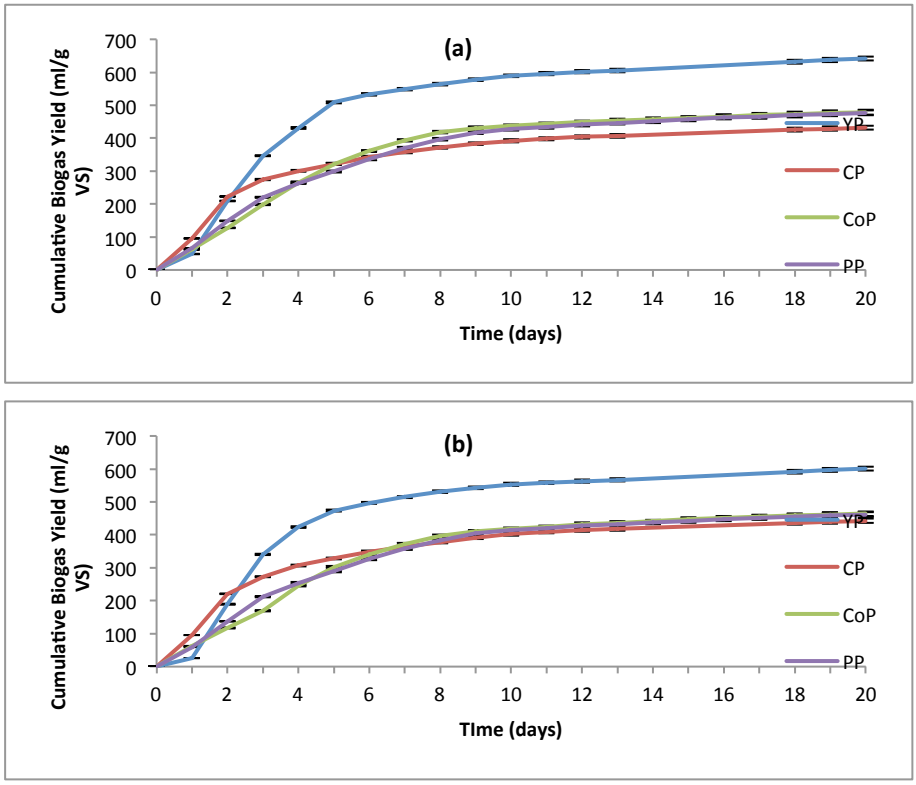


Figure 5–12 Results from duplicate test of cumulative biogas yields of Food Waste (a) Test 1 and (b) Test 2

5.3.3 Effect of Water Hyacinth on biogas yield of food waste

The Specific Biogas Yield of the food wastes were compared to the yields of their co-digested counterparts. For yam, cassava, cocoyam and plantain peels, co-digesting them with water hyacinth in the ratio 2:1 VS, reduced their biogas yields by 16, 22, 7 and 7%. The yam and cassava peels had a higher loss in biogas production compared to the cocoyam and plantain peels. The results are presented in Figure 5-13. There was no significant difference ($p<0.05$) between the biogas yields of the mono and co-digested samples.

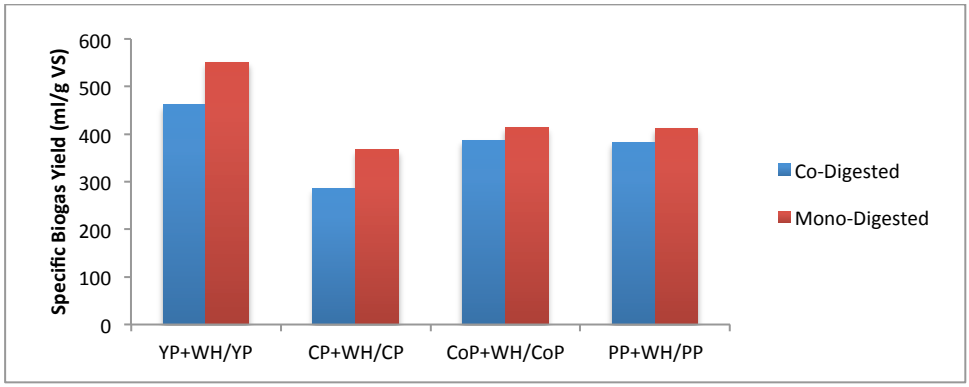


Figure 5–13 Specific Biogas Yields of Mono Digested Food Waste compared to Co-Digested Food Waste

Water Hyacinth has been shown to have recalcitrant nutrients (Mishima et al., 2008; Cheng et al., 2010; Chuang et al., 2011). These consist of lignin, cellulose and hemicellulose and AD microbes find it difficult to digest them, leading to its low yield. Despite this disadvantage, chemical pre-treatment of water hyacinth would break up the complex molecules freeing up nutrients for the microbes, leading to an increase in biogas production (Patil et al., 2011; Cheng et al., 2010; Gao et al., 2013; Cheng et al., 2013). Ganesh et al. (2005) extracted VFAs from water hyacinth using diluted cow dung. The process eliminated the indigestible fibres. Freeing up the nutrients has the possibility of increasing the biogas yields from co-digesting food waste with water hyacinth. Gunnarsson and Peterson (2007) suggested longer retention times for the plant, rather than expensive pre-treatment methods but in the case of water hyacinth, it is doubtful if longer retention times would free up the nutrients.

5.3.4 pH Values

The pH values for the food waste dropped within the first two days, indicating the presence of organic acids. The lowest pH on the second day was from the YP while the highest was from the CP. Afterwards there was a steady increase in value, eventually becoming steady by the tenth day. The results indicate that there was no adverse accumulation of VFAs. Similar to the co-digested substrates, the pH values vary between the values of 7 and 8.

5.3.5 Model Kinetics

The results of the process kinetics for the BMP of each food waste were determined and the results presented in Table 5-11.

Table 5–11 Kinetic Parameters and Simulated Biogas Yields of Mono-Digested Feedstock (means ± relative error of measurements)

	YP	CP	CoP	PP
Lag Phase, λ (days)	0.6 ± 0.1	0.0 ± 0.0	0.3 ± 0.0	0.0 ± 0.0
Rm (10^{-3} m^3/kg VS/day)	135.0 ± 2.1	88.0 ± 0.5	69.0 ± 3.1	63.0 ± 1.3
P (10^{-3} m^3/kg VS)	587.0 ± 20.9	406.0 ± 5.4	459.0 ± 7.0	455.0 ± 6.7
T80 (days)	5.3 ± 0.1	6.3 ± 0.1	6.8 ± 0.2	7.4 ± 0.0
R^2 (%)	95.4	97.0	97.5	97.0
R^2 Adj. (%)	93.9	96.1	96.7	96.0
RMSE	0.2	0.2	0.1	0.1
Biogas Measured (10^{-3} m^3/kg VS)	621.0 ± 20.6	437.0 ± 5.4	472.0 ± 7.5	470.0 ± 7.8
Biogas Predicted (10^{-3} m^3/kg VS)	587.0 ± 20.9	406.0 ± 5.4	459.0 ± 7.1	454.0 ± 6.7
% Difference	5.6 ± 0.2	7.1 ± 0.1	2.7 ± 0.0	3.3 ± 0.2

The lag phase ranged from 0 to 15 hours in all tests. As explained in Section 5.2, the inoculum had already been preconditioned and starved of nutrients. This led to an immediate consumption of added substrates leading to instant biogas production. The shortest T80 was by YP at 5.3 days. CP and CoP were next at 6.3 and 6.8 days. The longest period was for PP at 7.4 days. The T80 period for YP and CP increased by 14 and 34%, when co-digested

with water hyacinth. This indicates that water hyacinth has an antagonistic effect on YP and CP that led to an increase in their retention period. The T80 results were the same for both the mono and co-digestion of CoP and PP. Since the T80 can be used as a reference for the HRT, mono digested yam and cassava peels would spend less time being digested in an anaerobic digester than when co-digested with water hyacinth. The measured and simulated biogas production were compared and presented in Figure 5-14.

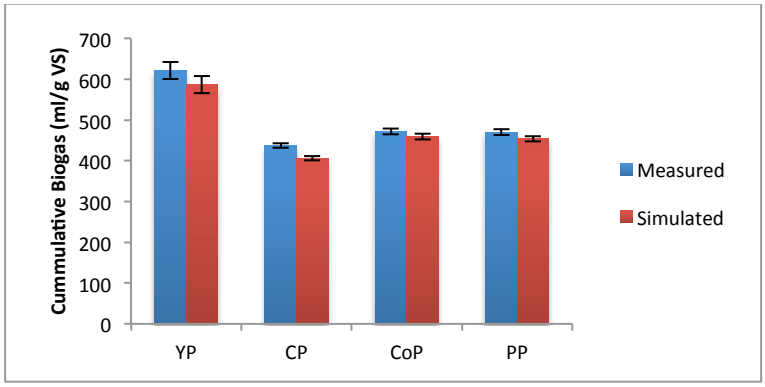


Figure 5–14 Measured and Simulated biogas yields of Mono-Digested Feedstock based on Modified Gompertz Model (Error bars indicating relative error of measurement)

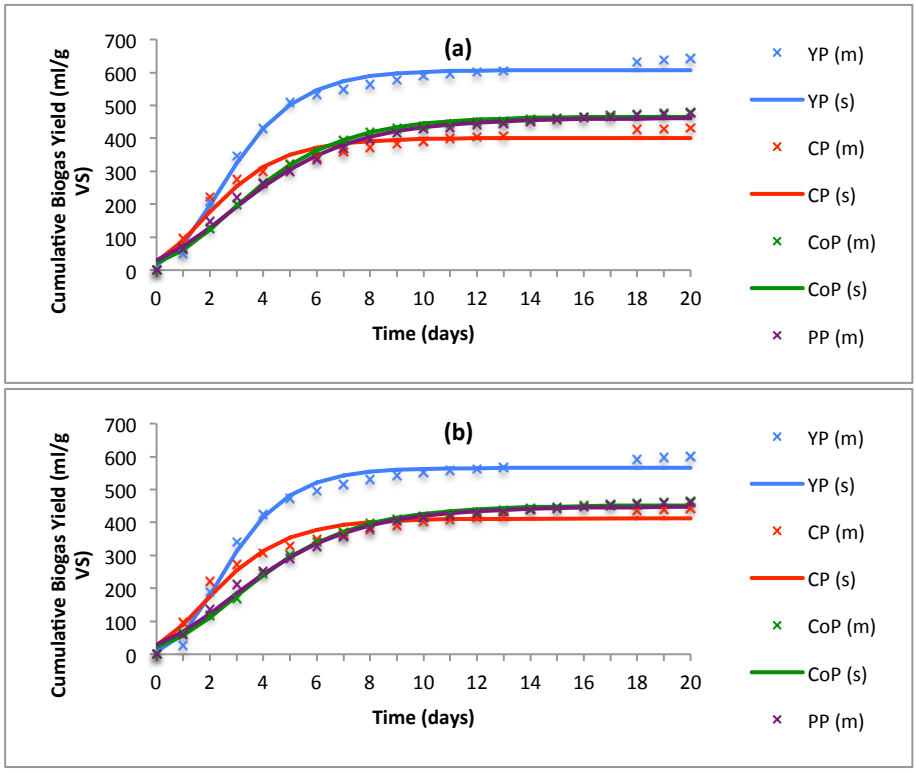


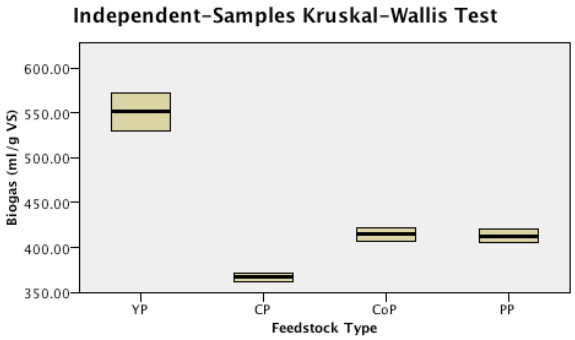
Figure 5–15 Results from duplicate test of Measured vs Simulated Biogas Production of Food Waste

Similar to the co-digested results, the measured biogas was more than the predicted values. The respective simulated biogas values of YP, CP, CoP and PP were 94%, 93% 97%, 97% of their measured values.

Figure 5-15 presents the measured and the simulated values and their closeness to fit. There was a good fit of the curves supported by R^2 values of 95.4% to 97.5%. This confirms that the measured values are in agreement with the simulated values. The mono-digested results have a better fit than their co-digested counterparts.

5.3.6 Statistical Analysis

Due to the small sample size of the groups, the distribution of the data cannot be verified to be normal. Also a visual analysis of the variance of the groups showed that the variances were unequal. Therefore a non-parametric Kruskal-Wallis test was performed on the results to determine if there was any significant difference between the samples. The results showed that there was no significant difference ($p<0.05$) between the groups. The results are shown in Figure 5-16 with test statistics in Appendix 10.



Total N	8
Test Statistic	6.167
Degrees of Freedom	3
Asymptotic Sig. (2-sided test)	.104

1. The test statistic is adjusted for ties.
2. Multiple comparisons are not performed because the overall test does not show significant differences across samples.

Figure 5–16 Kruskal-Wallis Analysis of Mono Digestion Results

5.3.7 Efficiency of Bio-reactor System

The efficiency of the system was determined using the same method as Section 5.2.8. and the results are presented in Table 5-12. The efficiencies of the bioreactor system using mono substrates are slightly higher than that of the co-substrates feedstocks because of higher biogas yields (and energy

output). Similar to the co-substrates they are too low to be used for any practical purposes besides BMP tests.

Table 5–12 Efficiency of bioreactor system using mono-digested feedstock as substrate

	Biogas (10^{-6} m^3)	Methane (10^{-6} m^3)	Energy system (kWh)	Efficiency (%)
YP	4.6	2.8	0.3	0.4
CP	3.1	1.9	0.2	0.2
CoP	3.5	2.1	0.2	0.3
PP	3.5	2.1	0.2	0.3

5.4 Biogas Production of Various States of Food Waste

This section presents the results from the BMP tests used to analyse the effects of moisture content and S:I ratios on biogas yields. The sample Dry YP 1:3 represent yam peel that has been dried and contains no moisture. The sample has an S:I ratio of 1:3 on VS basis. The sample Fresh YP 1:3 represent fresh weight yam peel containing an S:I ratio of 1:3 on VS basis. The Fresh YP 1:6 represent fresh weight yam peel mixed in an S:I ratio of 1:6.

5.4.1 Biogas Yields

The biogas yield results showed that moisture content and S:I ratio had impacts on gas production of food wastes. The results are presented in Table 5-13 while their Specific Biogas Yields are presented in Figure 5-17. The fresh weight sample produced more biogas than the dry sample. Fresh YP 1:3 produced 0.49 m^3/kg VS which was 7% more biogas than Dry YP at 0.46 m^3/kg VS. The results were in agreement with the findings of O'Sullivan et al. (2010) and Chanakya et al. (1993). However the findings contradict the results of Patil et al. (2011) whose study showed that dried water hyacinth produces more biogas than the fresh untreated plant. Comparing S:I ratios, Fresh YP 1:6 produced 0.52 m^3/kg VS, which was 6% more biogas than Fresh YP 1:3.

Table 5–13 Characteristics and Biogas Yield of various compositions of Yam Peel

	Dry YP 1:3	Fresh YP 1:3	Fresh YP 1:6
Total Solids (g)	8.7	8.7	8.7
Volatile Solids (g)	8.1	8.1	8.1
Crude Protein %VS	9.6	9.6	9.6
Crude Fibres %VS	7.00	7.00	7.00
Oils %VS	1.2	1.2	1.2
NFE %VS	82.2	82.2	82.2
Ash (g)	0.7	0.7	0.7
M (10^{-3} m^3/kg VS)	510.0	544.0	574.0
SBY (10^{-3} m^3/kg VS)	459.0	492.0	522.0
Effluent pH	7.9	7.9	7.8

The findings were in agreement with Cheng and Zhong (2014), Seno and Nyoman (2010) and Feng et al. (2013). The findings also hold true for

thermophilic digestion of food and green waste respectively (Liu et al., 2009). However the results are contradicted by those of Kafle et al. (2014) whose study analysed the digestion of Chinese cabbage waste under different S:I ratios. The findings showed that under both mesophilic and thermophilic conditions, increasing the S:I ratio from 0.5:1 to 2:1 led to an increase in biogas production.

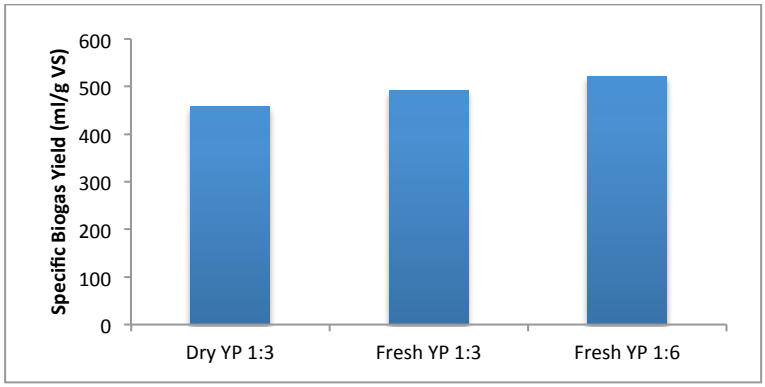


Figure 5–17 Specific Biogas Yields of various compositions of Yam Peel

Biogas yield of Fresh YP 1:6 was 95% of the Theoretical Biogas Potential of YP (0.55 m^3/kg VS). Fresh YP 1:3 and Dry YP 1:3 were 90% and 84% of the theoretical values. The high closeness to theoretical values in all cases can be interpreted to say that yam peel is an ideal feedstock for the AD process.

The daily biogas production is presented in Figure 5-18. From the graphs, Dry YP 1:3 reached its peak daily production on the second day which was faster than the two Fresh YPs that had their peaks on the third day.

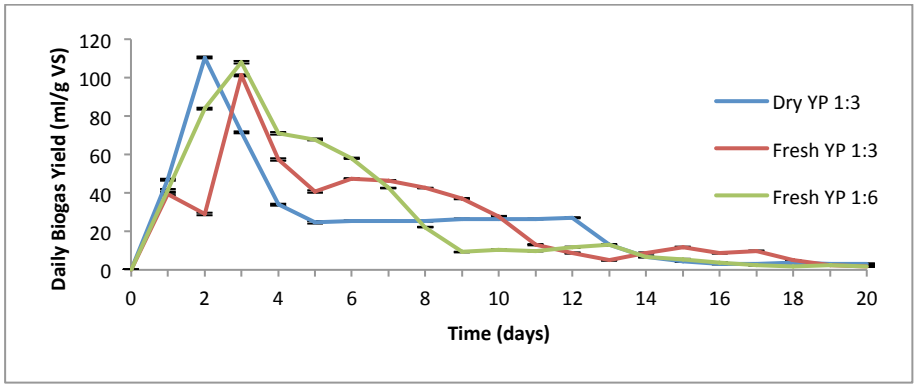


Figure 5–18 Daily Biogas Yield of various compositions of Yam Peel

The graph shows that the Fresh YP 1:3 had multiple peaks of gas production. Despite the dry sample reaching its peak production earlier, the cumulative production curve shown in Figure 5-19 shows that the fresh samples sustained a higher biogas production for the full test period. The Fresh YP 1:3 overtook the biogas production of the dry sample on the sixth

day, and continued with a higher production all the way to the end of the digestion period.

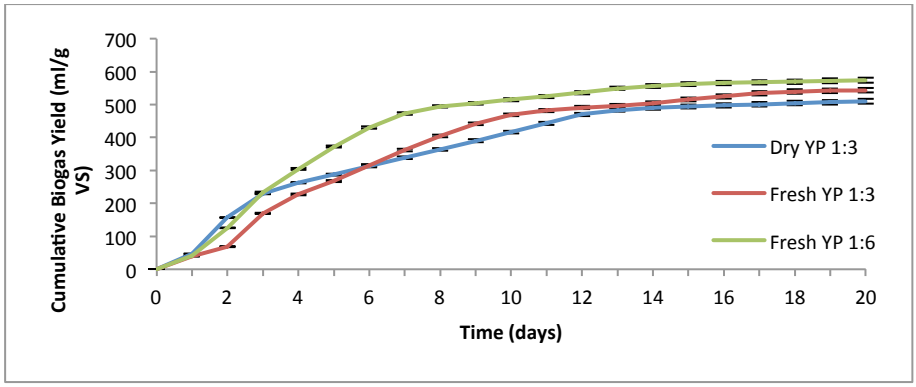


Figure 5–19 Cumulative Biogas Yields of various compositions of Yam Peel

5.4.2 pH Values

The pH values for the samples stayed within the 7 to 8 values. The dry sample maintained a lower pH value for longer than the fresh samples, but eventually rose to a higher value and ended up with the highest effluent pH of the three samples.

5.4.3 Model Kinetics

The biogas production kinetics for the samples are presented in Table 5-14.

Table 5–14 Kinetic Parameters and Simulated Biogas Yields of various compositions of Yam Peel

	Dry YP 1:3	Fresh YP 1:3	Fresh YP 1:6
Lag Phase, λ (days)	0.0	0.6	0.6
Rm (10^{-3} m^3/kg VS/day)	56.3	61.5	88.7
P (10^{-3} m^3/kg VS)	498.0	540.0	557.0
T80 (days)	9.7	8.8	6.7
R^2 (%)	99.2	98.0	95.6
R^2 Adj. (%)	98.9	97.3	94.1
RMSE	0.2	0.1	0.1
Biogas Production Measured (10^{-3} m^3/kg VS)	511.0	544.0	574.0
Biogas Production Predicted (10^{-3} m^3/kg VS)	495.0	537.0	556.0
% Difference	3.1	1.3	3.1

The Dry YP 1:3 had a lag phase of zero implying that its digestion and gas production started immediately. This is possibly as a result of the physical pre-treatment which increased the surface area and presented the substrate in a state that the microbes could easily access. The Fresh YP 1:3 however, had a lag phase of 15 hours. This indicated that it took time for the Fresh YP to be degraded to a state that the microbes could consume. From the results the moisture content has an effect on when gas production starts. Fresh YP 1:3 had a longer lag phase than Fresh YP 1:6. This was in line with findings by Gonzalez-Fernandez and Garcia-Encina (2009) which showed that an S:I ratio of 2:1 had a shorter lag phase than a ratio of 3:1. Meaning that having

a lower substrate proportion leads to an earlier onset of gas production. The T80 period for the Dry YP 1:3 at 9.7 days was longer than the T80 period for the Fresh YP 1:3 at 8.8 days. The significance is that fresh samples produce more biogas and it takes a shorter period of time to obtain the yield.

In the case of S:I ratio, the higher proportion of inoculum led to faster production of biogas compared to the sample with lesser inoculum. The findings were in agreement with results obtained by Gonzalez-Fernandez and Garcia-Encina (2009) whose findings showed that increasing the substrate proportion led to a decrease in methane production. This drop in yield was attributed to an accumulation of VFAs which adversely affects biogas production. The measured and simulated biogas production of the samples were presented in Figure 5-20. In all tests, the measured values were higher than the simulated values.

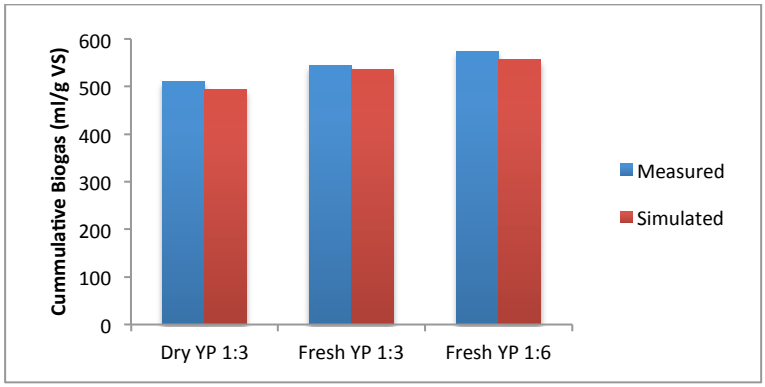


Figure 5–20 Measured and Simulated biogas yields of various compositions of Yam Peel based on Modified Gompertz Model

Figure 6-21 shows the closeness in fit between the measured and the simulated values. The results indicate that the values are in agreement with each other with R^2 values as high as 0.992 for Dry YP 1:3.

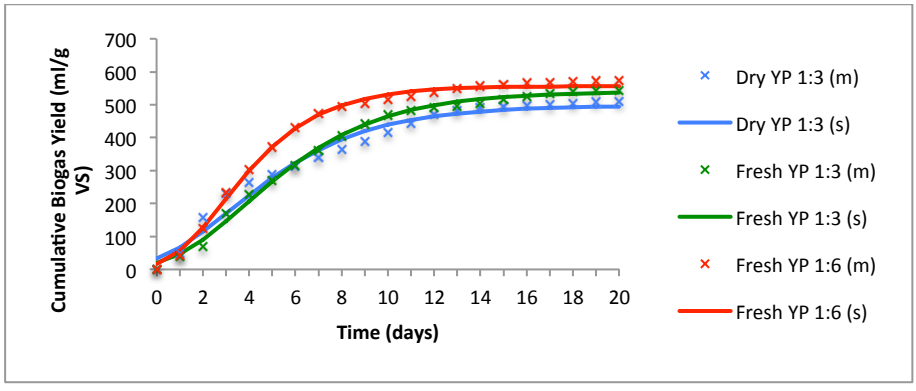


Figure 5–21 Measured vs Simulated Biogas Yields of various compositions of Yam Peel

5.4.4 Biogas Composition

This section presents the methane, carbon dioxide and propane content over the 20-day period. The samples were automatically analysed every 15

minutes and the results are presented in Figure 5-22. To reduce the visual effect of noise, the average daily contents of the gases were presented in Figure 5-23.

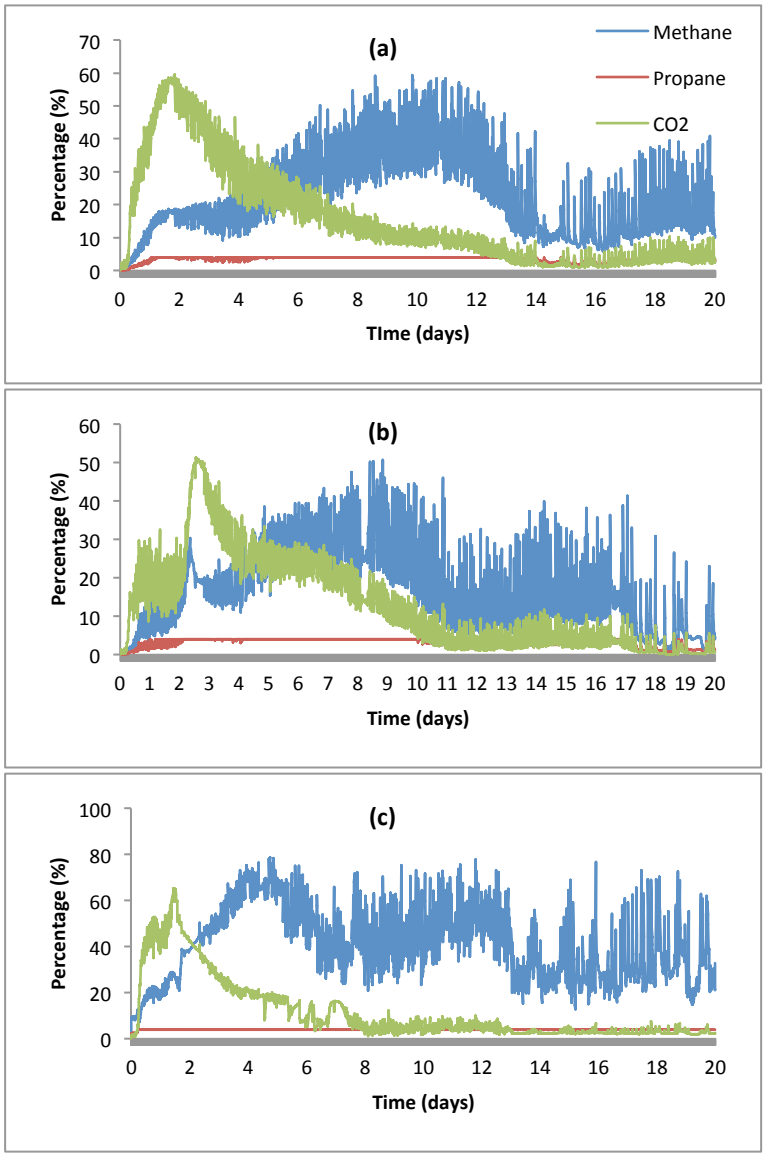


Figure 5–22 Biogas composition every 15 minutes of (a) Dry Yam Peel in the ratio 1:3 (b) Fresh Yam Peel in the ratio 1:3 (c) Fresh Yam Peel in the ratio 1:6

The results are in line with earlier findings that show an initial higher carbon dioxide content in the biogas which is later surpassed by methane. The Dry YP 1:3 and Fresh YP 1:3 both crossed that threshold on the sixth day. Comparing the Fresh YP 1:3 and Fresh YP 1:6, the higher inoculum content led to higher average daily methane content by as early as the third day. This was achieved in half the time that it took the sample with half the inoculum. Indicating that S:I ratio affects the progress of methanogenic activity.

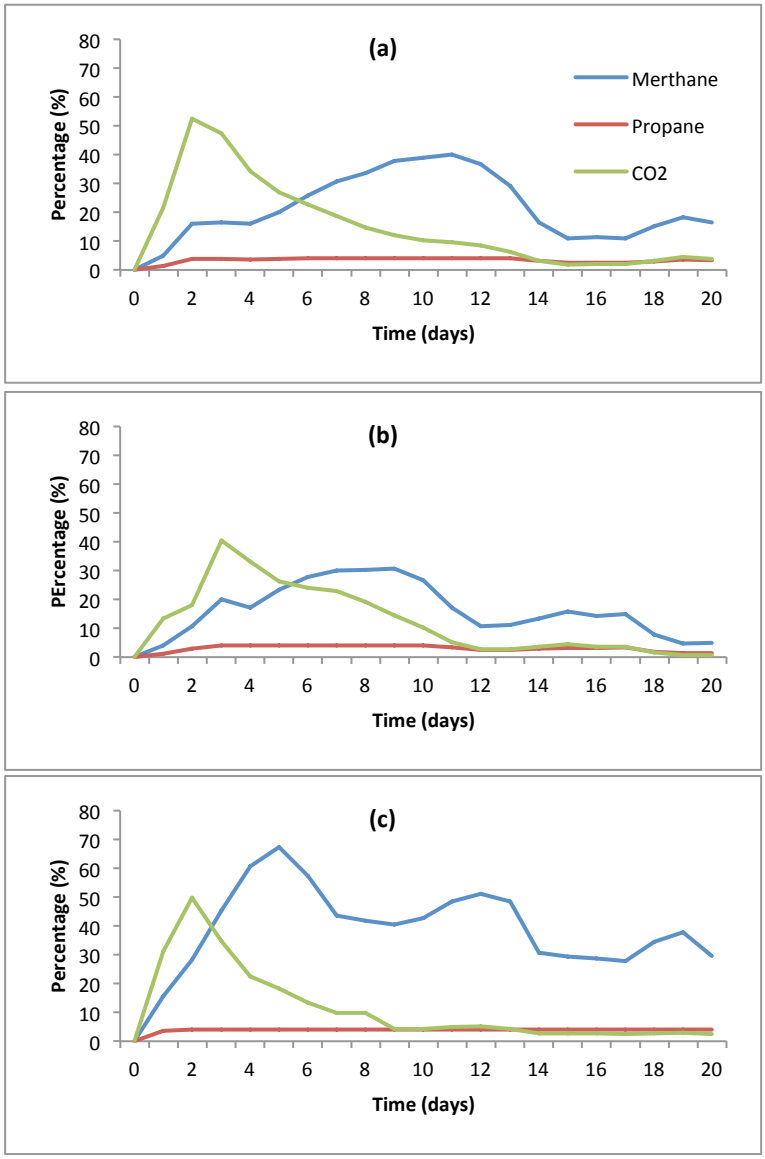


Figure 5–23 Moving Average Daily Biogas composition of (a) Dry Yam Peel in the ratio 1:3 (b) Fresh Yam Peel in the ratio 1:3 (c) Fresh Yam Peel in the ratio 1:6

The average methane content during the various stages of digestion are presented in Table 5-15.

Table 5–15 Average Methane content over various stages of retention time for various compositions of Yam Peel

Sample	T80 period (days)	Average % CH_4 T80 period (%)	Average % CH_4 rest of digestion time (%)	Average % CH_4 full digestion time (%)
Dry YP 1:3	9.7	23	21	22
Fresh YP 1:3	8.8	21	13	17
Fresh YP 1:6	6.7	46	38	41

The Dry YP 1:3 had a higher methane concentration than the Fresh YP 1:3. This indicates that the dry sample is more favourable for methanogenic activity. When comparing Fresh YP 1:3 and Fresh YP 1:6, doubling the amount of inoculum leads to more than twice the methane content. The Dry YP 1:3 had its highest average daily methane content on the eleventh day at 40%. The Fresh YP 1:3 was on the ninth day at 31% while the Fresh YP 1:6 had its highest methane content as early as the fourth day at 67%.

5.5 Chapter Summary

This chapter presented the results of the bio-methane potential tests. The bioreactor configuration tests showed that the first configuration suffered from gas leaks and other system design flaws. While the second and third configurations worked effectively for AD tests. An analysis of the costs of the second and third configuration bioreactors showed that, the multi-reactor is nine times cheaper than buying nine of the single reactors. For energy consumption, the multi-reactor would consume 3.7 times less energy than nine of the single reactors.

The results of the anaerobic co-digestion of the food wastes showed that YP+WH had the highest biogas yield at 0.42 m^3/kg VS. Next were CoP+WH and PP+WH at 0.39 m^3/kg VS and 0.38 m^3/kg VS respectively. CP+WH had the lowest yield at 0.29 m^3/kg VS which was due to its cyanide content. YP+WH had the highest biodegradability at 76%. Next were CoP+WH and PP+WH which had values of 70% and 69% respectively. Least biodegradable was CP+WH, which had a very low value of 48%. The technical digestion time for YP+WH was shortest at 6 days while CP+WH was longest 8.4 days. The highest methane content of biogas was obtained during the T80 period.

The results of the mono-digestion of the food waste showed that YP produced the highest Specific Biogas Yield of 0.55 m^3/kg VS. Next were CoP and PP at 0.41 m^3/kg VS. The least yield was from CP at 0.37 m^3/kg VS. YP had the highest biodegradability at 100%. Next were CoP and PP at 75% and 73% respectively. The lowest was CP at 59%. A comparative analysis of the co and mono digestion results shows that water hyacinth causes a drop in biogas yields ranging from 7 to 22%. This was attributed to the complex indigestible molecules in the plant. Further results showed that fresh food waste produces 7% more biogas than dried food waste while halving the S:I ratio increases the biogas production by 6%.

This chapter has presented the results and analysis of the various tests conducted in this study. The discussions have provided fresh insight on the biogas potential of Niger Delta food waste. The findings indicate that the food wastes are suitable feedstock for the anaerobic digestion process. The next chapter will present the conclusions of the study.

Chapter 6 Conclusion

There is currently limited reported data on the anaerobic digestion of region-specific food waste from the Niger Delta. Few research studies have been conducted on the biogas potential of the peels of yams, cassavas, plantains and other local food wastes. The available studies showed that local researchers did not utilise any standard scientific method for their BMP tests. This leads to limited low quality data on a potentially abundant supply of renewable energy feedstock. In addition there is no data on the Specific Waste Index of any of the locally consumed foods.

Subsequently standard experimental methods were used to obtain the required data on these new set of feedstock. The study focused on the waste characterisation of the food waste, their theoretical biogas potential, and the specific biogas potential of the most common food waste. The data collection was focused on biogas yields and methane content because that is the most useful preliminary data prior to the deployment of AD technology in the region. The Specific Waste Index values for the various foods were obtained using local food preparation methods.

This study identified nine locally consumed foods in the Niger Delta based on consumption patterns. The most commonly consumed of the foods are yams, cassava, cocoyam and plantain. Next an effective and cheap bioreactor system was designed for this study and for use in simple Nigerian laboratories. The system was used to perform BMP tests on the common food waste and water hyacinth using VDI 4630 guidelines. Finally the local policies and regulations that would facilitate the implementation of the findings of this study were presented.

The following main findings and conclusions can be drawn from the results of the research:

6.1 Main Findings

6.1.1 Food Waste Content

The findings in this section identify the common food waste in the Niger Delta and present their waste content.

- Nine common local foods were identified for the Niger Delta consisting of yams, cassava, cocoyam, plantain, corn, egusi, beans, groundnut and ugwu having waste contents of 25%, 20%, 24%, 34%, 59%, 19%, 23%, 24%, 37% respectively.
- All the nine foods tested had Specific Waste Indexes that varied from 0.2 to 1.5. Corn had the highest range at 1.4-1.5, which is made up of both

the cob and husk. When considered on a regional scale these foods would provide a significant amount of organic waste that can serve as feedstock for the anaerobic digestion process.

- Corn, plantain and ugwu have high waste contents, which have low organic fractions of 30%, 14% and 7%. However egusi and groundnut have low waste contents that have high organic proportions of 80% and 78%. When considering food waste for anaerobic digestion, the total waste content and its organic fraction have to be taken into consideration.
- The four most commonly consumed foods in the Niger Delta are yams, cassava, cocoyam and plantains.

6.1.2 Waste Characterisation and BMP of Food Waste

The findings in this section address the waste characteristics and theoretical bio-methane potential of the nine region specific food wastes and water hyacinth.

- The nine food wastes had a wide range of Total Solid content. The lowest were 7% and 8% for water hyacinth and ugwu stalk while the highest were 82% and 81% for egusi shell and groundnut husk.
- All the food waste samples have VS/TS values above the recommended value of 70% for AD substrate. This confirms their suitability as feedstock for biogas production.
- Water hyacinth and ugwu stalk had the highest moisture, crude protein and ash contents. While egusi shell and groundnut husk had the lowest moisture, crude protein contents and highest volatile solid contents.
- The peels from the tubers and plantain had the highest NFE content, ranging from 59 - 82%.
- Cassava peels have the highest oil content by a large margin at 25%. This comes as a result of wax coatings used by locals to prevent the tuber from undergoing rapid deterioration.
- The theoretical biogas yields of the nine samples range between (540 – 619) x 10^3 m^3/kg VS which is an acceptable range for AD feedstock.
- Cassava peel has the highest theoretical biogas yield on VS basis at 619 x 10^3 m^3/kg VS while egusi shell has the highest potential yield on a fresh weight basis of 460 m^3/tonne FW. The ugwu stalk has the highest potential methane content at 58%.
- There is a direct relationship between the TS and VS content of feedstocks and their potential biogas yield on a fresh weight basis. The higher the TS or VS, the higher the biogas yield. Hence if two samples are obtained, the knowledge of their TS or VS can be used to determine which sample has a higher biogas potential.

6.1.3 Food Waste Quantification and Bioenergy Potential of the Niger Delta

This section provides the findings of the waste quantification and renewable energy potential of the Niger Delta.

- Based on consumption and expenditure patterns, tubers and plantains are the most consumed foods in the Niger Delta, with yam and cassava consumed on a daily basis by 70% of the population. These foods have the potential of producing high volumes of food waste in the region.
- The total projected amount of food waste from the eight foods (ugwu not included) in the Niger Delta by 2020 is 2.6 – 4.1 (10^6) tonnes. Corn is the highest contributor to that amount as a result of its high waste content and frequent consumption.
- The total projected energy derived from the anaerobic digestion of the eight food wastes in the Niger Delta region is 2.5 – 3.9 TWh/year. Corn waste is also the highest contributor to the energy mix.

6.1.4 Bioreactor Configurations

This section presents the findings on the cheap and effective bio-reactor configuration.

- An effective bioreactor system that can perform standard BMP tests can be built that costs less than 15% of the market value of conventional bioreactors.
- The low efficiency of a laboratory scale bioreactor makes it useful for Bio-methane potential tests and not for any practical power generation.
- One of the major challenges in building a bioreactor is addressing the gas leaks.

6.1.5 Bio-Methane Potential Tests

This section presents the findings of the bio-methane potential tests conducted.

- Of the four most common foods co-digested with water hyacinth, YP+WH has the highest specific biogas yield of 0.42 m^3/kg VS. The second highest is CoP+WH at 0.39 m^3/kg VS while the next is PP+WH at 0.38 m^3/kg VS. The lowest yield came from CP+WH at 0.29 m^3/kg VS.
- Mono-digested YP has the highest specific biogas yield of 0.55 m^3/kg VS while CP has the lowest at 0.37 m^3/kg VS. CoP and PP each have 0.41 m^3/kg VS.
- Co-digesting food waste with water hyacinth is antagonistic to the digestion process leading to a drop in biogas productivity. Gas yields dropped for yam, cassava, cocoyam and plantain peels by 16, 22, 7 and 7% respectively when co-digested with water hyacinth.

- YP+WH had the highest degradability of the co-digested substrates at 76% while CP+WH was the least biodegradable at a very low value of 48%. For the mono-digested substrates, YP had the highest biodegradability at 100%, indicating positive synergic activities, while the lowest was CP at 59%. The mono-digested substrates had better biodegradability results than the co-digested samples.
- The ranking based on biogas yields of the four food wastes varies from the ranking based on theoretical biogas yields. This implies that there are other factors that have an impact on biogas yields other than nutrient content alone. These include bioavailability of complex nutrients for microbes and process inhibitors.
- Cassava peels have the lowest biogas yields of all the samples. This is attributed to its cyanide content, which is toxic to microbes.
- The ranking of measured biogas yields was closely related to the ranking based on Nitrogen Free Extract content. This indicates that samples with a higher NFE content produce higher yields of biogas.
- Methane content of biogas varies throughout the digestion period. Consequently multiple biogas analysis tests should be conducted throughout the duration of a BMP test. The highest methane content is obtained during the T80 period and can have up to twice the methane content of the rest of the digestion period.
- In all the tests, the initial biogas composition consisted more of CO_2. After a few days, the CH_4 became the dominant gas. This indicates that intermediaries had to be formed before the methanogens started converting them to methane.
- The kinetic results of the BMP tests show that acclimatising the inoculum for a week prior to digestion creates a hunger phase for the microbes. This causes an immediate consumption of added substrates leading to a rapid onset of biogas production. The result is low lag phases ranging from 0 to 15 hours.
- The T80 period for YP and CP increased by 14 and 34%, when co-digested with Water Hyacinth. This indicates that Water Hyacinth has some antagonistic effect on YP and CP that causes an increase in their digestion retention period.
- Fresh food waste produces 7% more biogas than dried food waste while halving the S:I ratio increases the biogas production by 6%.
- Digesting food waste in the S:I ratio of 1:2 provides sufficient buffer to prevent a drop in pH by organic acid accumulation which may lead to digester failure.
- The biogas production potential, P, is the most sensitive parameter of the Modified Gompertz Model.

6.1.6 Local regulations and policies

- Regulations and policies relating to the utilisation of AD technology apply to plants whose power output is above 1 MW. In order to deploy such AD technologies, multiple plants each having power outputs lower than 1 MW should be utilised to benefit from the regulatory exemption.
- There are financial incentives including tax credits to encourage the adoption of renewable energy technologies and rural electrification.
- Functions of various regulating agencies overlap one another.

6.2 Implications and Limitations of Study

6.2.1 Implications of Study

- Standard BMP tests can be performed with low-cost effective bioreactors. Hence the energy potential of other country-specific food wastes can be performed.
- The nutrient characterisations of the food wastes were performed, giving researchers the information required to utilise the samples for other bio-chemical processes.
- The results from this study can serve as the foundation for a comprehensive AD feedstock database that provides the energy potential of other region specific food wastes.
- Policy makers and renewable energy investors now have the data of the bioenergy potential of common Niger Delta food wastes and have the option of promoting the use of the waste with the highest potential.
- Researchers have information on the antagonistic effects of co-digesting water hyacinth with food waste.

6.2.2 Experimental and Deployment Limitations

- Inability to obtain actual food samples from the Niger Delta as a result of regional instability. Similar samples were obtained from specialised food markets in the UK.
- Inability to perform biochemical analysis of digester contents as a result of unavailability of specialised equipment.
- The scarcity of local data led to adoption of assumptions in the quantification of the regional food waste and renewable energy potential.
- Low number of experimental replications leading to small sample sizes that may lead to sampling errors.
- Some of the biogas produced might be absorbed in the water used to measure gas production, leading to a lower biogas production result than was actually produced.
- The NDIR gas sensor was susceptible to interference, leading to a lot of noise in the output of the methane and carbon dioxide content.

- There will be challenges in obtaining segregated food waste from the local inhabitants. The waste will most likely be a mixture of the different food wastes.
- Obtaining sites to build the bioreactors will prove difficult due to the limited usable land area in the swampy Niger Delta.
- There needs to be a design and analysis of the right type of the gas to power generating system that should be incorporated to the digester.
- Despite these limitations, the research was successfully carried out.

6.3 Bioreactor Scale Up

The building of biogas plants comes with substantial economic risks, especially when utilising unknown feedstock. To minimise financial and logistical risks, Anaerobic Digestion experiments are preformed at the laboratory scale using bioreactors rather than using industrial scale plants. These tests provide the Bio-Methane Potential of the feedstock. It is essential to know how laboratory bioreactors can be scaled to an industrial scale when planning and building a new plant. Ideally the exact same type of feedstock and inoculum should be used for both the laboratory and industrial scale digesters. Also similar process parameters have to be observed for both systems. These include temperature, substrate to inoculum ratio, organic loading rate, retention time and mixing. The shape and volume aspect ratio of the reactor vessel and the digester plant have to be identical. As scale increases, tank geometry influences the homogeneity of the digester. Additionally the geometric characteristics of the digester directly influences the mixing of a digester, which in turn influences heat and mass transfer of the reactants. As aspect ratios increase, mixing times will also increase. In scaling up, the following methods can be used:

Simple Scale-Up Method: This method utilises scale up inputs that are maintained between the laboratory scale and industrial scale systems. These include Constant Power input per unit volume, Constant Volumetric Mass Transfer Coefficient and Constant Impeller Tip Speed for scaled up systems.

Computational Fluid Dynamics: This method utilises mathematical models to simulate the scaled up interaction of liquids and gases in bioreactors. The analysis determines the hydrodynamic effects of scaling up bioreactor systems.

Dimensionless Analysis: This is mathematical method utilises dimensionless groups to predict physical parameters that influence fluid mechanics. Such groups include Power and Reynold's Numbers which link reactor mixing and fluid properties for scaled-up of systems. The aim of this method is to keep the dimensionless groups constant during scale-up so that the mechanisms of the bioprocess are not changed.

The various methods strive to maintain the same biogas potential between laboratory scale systems and industrial plants. But no matter the perfection of method used, there are usually deviations between the results from the scales. In some cases, there are synergetic benefits from the scaled up system that results in increased biogas production while in others, gas production drops.

6.4 Recommendations and Future Work

6.4.1 Recommendations

Food wastes should not be co-digested with water hyacinth unless its recalcitrant molecules have been broken down by pre-treatment.

The duration of the BMP tests for food waste can be shortened as a result of the short technical digestion times which never exceeded nine days.

Future BMP tests should be conducted with fresh samples since they produce more biogas yields than dried samples. Also if the test will be performed in the Niger Delta, eliminating the drying process will also conserve the limited available energy.

The biogas should be dried prior to being passed through the NDIR sensor to reduce interference from the water vapour content of the biogas. Errors from the interference lead to noise in the output.

The NDIR biogas analyser is relatively cheaper compared to the expensive conventional gas chromatographs. Nonetheless the sensor could still be quite expensive for Nigerian laboratories. Future tests should utilise the Liquid Displacement Method for measuring the methane content of biogas. If successful, the method will save costs of purchasing the inline NDIR sensors, which is one of the most expensive components of the bioreactor system.

6.4.2 Future Work

During the pursuit of my research, all of my aims were achieved, as shown in earlier sections of this chapter. However further studies are required to progress this area of research.

Biogas production of food waste was shown to reduce when co-digested with water hyacinth. The co-digestion tests should be repeated with chemically pre-treated water hyacinth to determine if the biogas production will drop, increase or remain the same.

The BMP tests were performed using microbes that were not acclimatised to the exotic food waste. Tests should be performed using acclimatised inoculum to determine the effect on biogas production. Also various S:I ratios

should be used for tests to determine the optimum value for the highest biogas yields of the food wastes.

All the various food wastes should be digested together to determine the effect on gas production.

To confirm the findings of this study, a pilot study of food waste collection in a rural community and its utilisation as a feedstock for a full-scale operational AD plant should be performed. This will ascertain the feasibility of adopting such methods for renewable energy production.

This section ends the thesis. Next the references that were cited in this thesis are listed.

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Appendices

Appendix 1: Baserga Model Equations

Digestibility factors:

Crude Fibre	*(C_rFd)*	*74.3%*
Crude Protein	*(C_rPd)*	*65.09%*
Crude Fat	*(OAHd)*	*67.51%*
NFE	*(NFEd)*	*69.97%*

Gas Yield Conversion Factors:

Carbohydrates	*(GYCf)*	*790 l/kg*
Proteins	*(GYPf)*	*700 l/kg*
Fat	*(GYOf)*	*1250 l/kg*

Methane content of Biogas:

Carbohydrates	*(MCf)*	*50%*
Proteins	*(MPf)*	*71%*
Fats	*(Mof)*	*68%*

Calculated Parameters

$NFE = 100 - (C_rP + C_rF + OAH + Ash + Moisture)$

$VS = (C_rF + C_rP + OAH + NFE)$

Baserga Equations:

$Digestible\ Carbohydrate\ \left(\frac{g}{kg}DMB\right)\ DC = ((C_rF \times C_rFd) + (NFE \times NFEd))/10$

$Digestible\ Crude\ Protein\ \left(\frac{g}{kg}DMB\right)\ DP = (C_rP \times C_rd)/10$

$Digestible\ Crude\ Fat\ \left(\frac{g}{kg}DMB\right)\ DO = (OAH \times OAHd)/10$

And :

$Digestible\ Carbohydrate\ \left(\frac{kg}{kg}VS\right) DCv = DC/(VS \times 10)$

$$Digestible\ Crude\ Protein\ \left(\frac{kg}{kg}VS\right)\ DPv = DP/(VS\times 10)$$

$$Digestible\ Crude\ Fat\ \left(\frac{kg}{kg}VS\right)\ DOv = DO/(VS\times 10)$$

And :

$$Gas\ Yield\ Carbohydrate\ \left(\frac{l}{kg}VS\right)\ GYC = DCv\times GYCf$$

$$Gas\ Yield\ Proteins\ \left(\frac{l}{kg}VS\right)\ GYP = DPv\times GYPf$$

$$Gas\ Yield\ Fat\ \left(\frac{l}{kg}VS\right)\ GYO = DOv\times GYOf$$

$$\boldsymbol{Total\ Gas\ Yield\ \left(\frac{l}{kg}VS\right)\ TGY = GYC + GYP + GYO}$$

And :

$$Methane\ Share\ for\ Carbohydrates\ (\%)\ MC = GYC\times MCf/TGY$$

$$Methane\ Share\ for\ Protein\ (\%)\ MP = GYP\times MPf/TGY$$

$$Methane\ Share\ for\ Fats\ (\%)\ MO = GYO\times MOf/TGY$$

$$\boldsymbol{Total\ Methane\ Content\ (\%)\ TMC = MC + MP + MO}$$

And :

$$\boldsymbol{Gas\ Yield\ \left(\frac{m^3}{tonne}of\ Fresh\ Matter\right) = (TGY\times VS)/100}$$

Appendix 2: Calculations for Waste Quantification and Bioenergy Potential of the Niger Delta

The following calculations will be done for each food item, and then summed up to get the value for the whole region.

Calculations:

Annual Consumption per individual (kg) = daily consumption (kg) × Weekly consumption freq. ($week^{-1}$) × 52 (weeks)

Annual consumption of population (kg/yr) = Annual consumption per individual (kg) × Population

Annual Food Waste (kg/yr) = Annual Consumption of Pop. (kg) × Waste Content of food (%)

Annual Biogas (m^3/yr) = Annual Food Waste (tonnes) × Total Gas Yield of waste (m^3/tonne)

Annual Methane (m^3/yr) = Annual Biogas (m^3) × Methane Content (%)

Annual Energy (MJ/yr) = Annual Methane (m^3) × Gross Calorific Value Methane (MJ/m^3)

Annual Elect. Energy (kWh/yr) = Annual Energy (MJ) × 0.2778 kWh/MJ

Constants

Gross Calorific Value Methane = 38 MJ/m^3

1 MJ = 0.2778 kWh

Appendix 3: Calculations for heat loss from shaking water bath.

An assumption is made that the air has a temperature of 15.5 C and is still not flowing.

Temperature of water	*37^0C*
Surface area of water (minus circumference of 9 vessels)	*$0.078m^2$*
Surface area of steel tank in contact with water	*$0.448m^2$*
Evaporation heat loss at 37C	*$0.50kW/m^2$*
Radiation heat loss at 37C	*$0.22kW/m^2$*
Heat loss through steel insulated bath wall	*$0.05kW/m^2$*
Hours in 20 days (duration of experiment)	*480 hours*

(Heat loss values taken from heat loss table for open water tanks (Engineering Toolbox, 2016) and converted to metric units.

$Q_{evaporation} = (0.50 \times 0.078)kW = 0.039kW$

$Q_{radiation} = (0.22 \times 0.078)kW = 0.017kW$

$Q_{transmission} = (0.05 \times 0.448)kW = 0.022kW)$

Hence, $Q = (0.039 + 0.017 + 0.022) = 0.078kW$

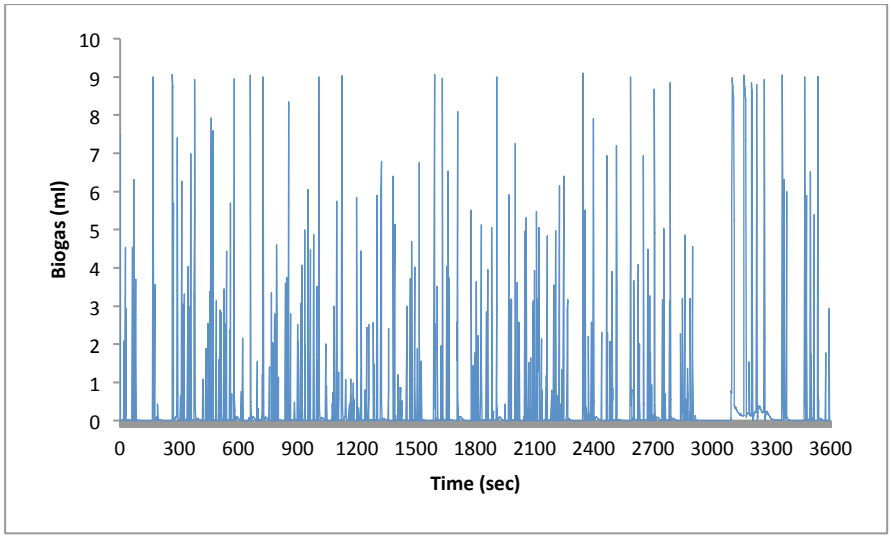
For the duration of the project, the energy loss is:

$Q = (0.078 \times 480)kW \times 480h = 37.44kWh$

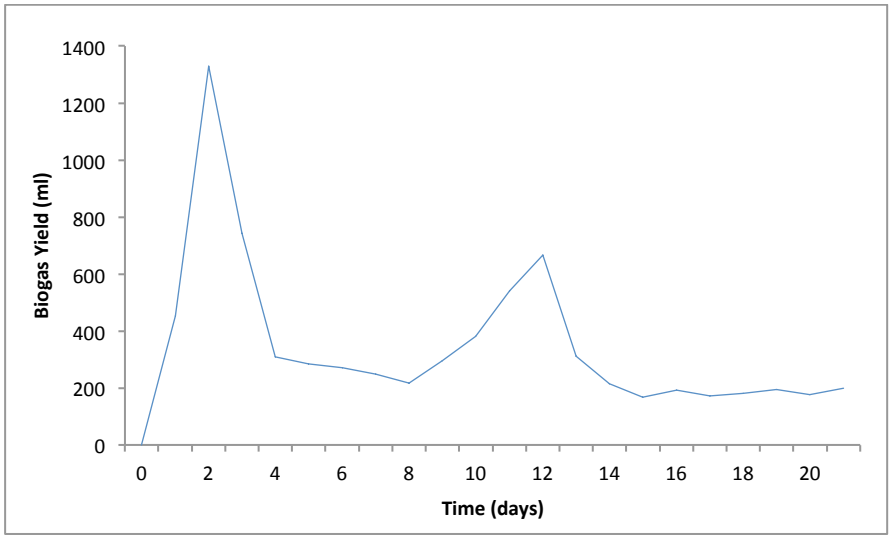
Appendix 4: Instantaneous Biogas Production

The results of a biogas experiment using the configuration system for fresh yam peel with the S:I of 1:3. Temperature of the reactor is 37.5^{O}C and the magnetic stirrer speed is 350 rpm.

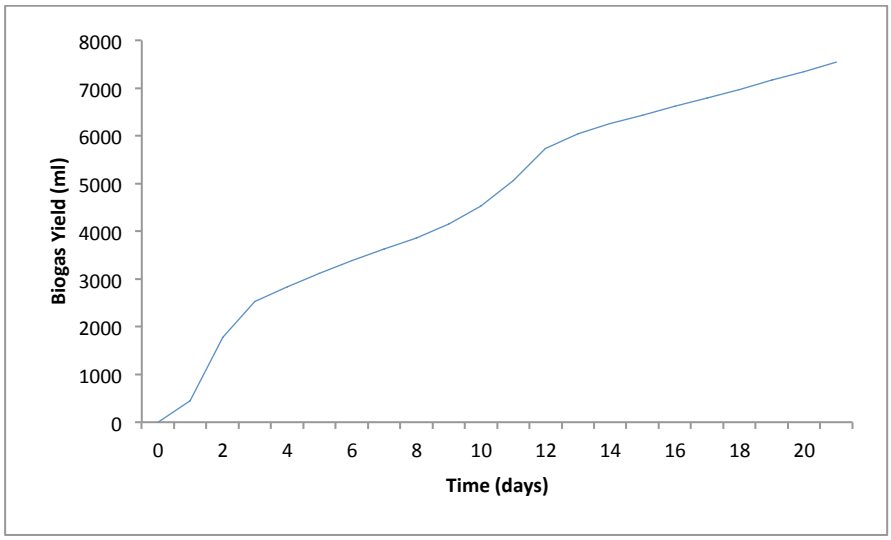
Appendix Figure 1 shows the instantaneous biogas production over a period of one hour on the second day of biogas production. It shows continuous fluctuations in biogas yield over the whole time frame. Appendix Figure 2 and Appendix Figure 3 present the daily and cumulative biogas yields respectively over the duration of the test. Appendix Figure 4 and 5 show the variations in biogas composition and pH values.



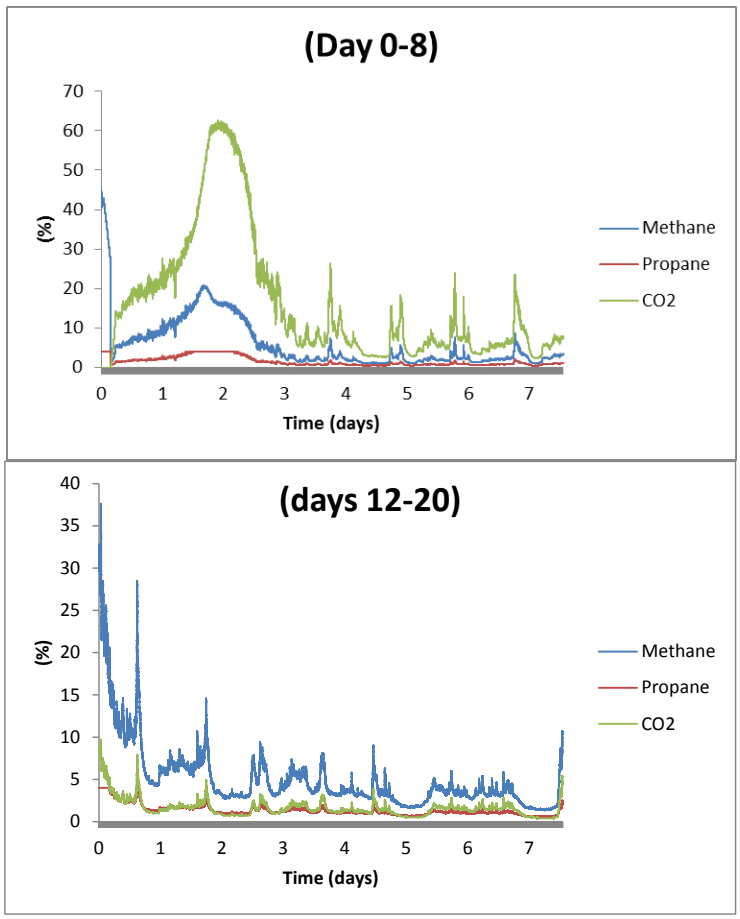
Appendix Figure 1 Instantaneous Biogas Yield over one hour period



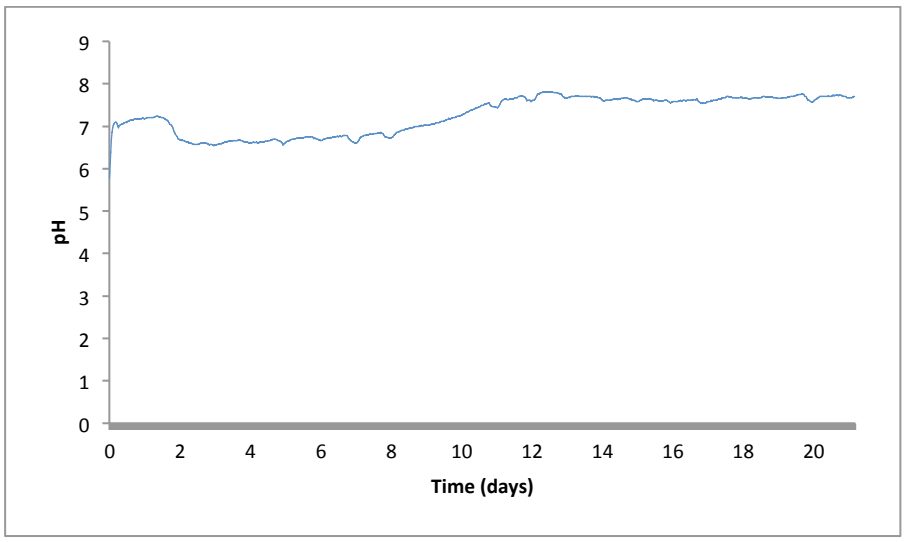
Appendix Figure 2 Daily Biogas Yield



Appendix Figure 3 Cumulative Biogas Yield



Appendix Figure 4 Biogas Composition



Appendix Figure 5 pH Values

Appendix 5: Anaerobic Digestion Microorganisms

AD microorganisms their substrates and products are presented from (Argyropoulos et al., 2013a and Argyropoulos et al. 2013b;

1 Hydrolytic

Lignin

Fungi: Botrytis, Phanerochaete
Actinomycetes: Nocardia, Microbacterium, Streptomyces.
A-Protobacteria: Brucella, Ochrobactrum, Paracoccus
γ-Protobacteria: Acinitobacter, Escherichia, Pseudomonas

Celluloses

Fungi: Trichoderma, Fusarium, Penicillium, Aspergillus
Bacteria: Bacillus, Clostridium, Pyrococcus, Streptomyces

Hemicelluloses

Fungi: Trichoderma, Aspergillus, Fosarium, Penicillium
Bacteria: Bacillus, Butyrivibrio, Clostridium, Fusobacterium

Pectins

Fungi: Aspergillus, Fusarium, Penicillium
Bacteria: Bacillus, Clostridium, Fusobacterium

Proteins

Bacteria: Bacteroides, Campylobacter, Clostridium, Fusobacterium, Peptococcus, Selenomonas, Streptococcus

Lipids

Bacteria: Anaerovobrio, Clostridia, Micrococcus, Syntrophomonas

2. Acidogenic

- Clostridium produces acetone, butanol, ethanol, butyrate, hydrogen and carbon dioxide.
- Enterobacter produces acetate, butylene, ethanol, glycol, lactate, hydrogen and carbon dioxide.
- Lactobacillus produces lactate
- Escherichia produces acetate, ethanol, lactate, hydrogen and carbon dioxide.

- Propionibacterium produces propionate.

3. Acetogenic

Bacteria: Acetobacterium, Sporomusa, Clostridium, Ruminococcus, Eubacterium, Thermoanaerobacter, Treponema, Moorella thermoacetica,

δ–Proteobacteria: Desulfotignum phosphitoxidans

4. Methanogenic

Methane producing Archaea of the phylum Euryarchaeota have 6 orders of: Methanosarcinales, Methanococcales, Methanomicrobiales, Methanosarcinales, Methanopyrales, Methanocellales and 31 genera of: Methanosarcina, Methanobrevibacter, Methanobacterium, Methanosaeta. (Argyropoulos et al. 2013b)

Methanobacterium formicium that utilises formate (methanoate: $CHOO^-$), carbon dioxide and hydrogen.

Methanobacterium thermoantotrophicum that utilises carbon monoxide, carbon dioxide and hydrogen.

Methanococcus frisius that utilises methanol, methylamine and hydrogen.

Methanococcus mazei that utilises methanol, methylamine and acetate.

Methanosarcina bakerii that utilises methanol, methylamine, acetate, carbon dioxide and hydrogen.

Appendix 6: Digestate Analysis of Inoculum Source

The results of the multiple analysis of the digestate from the Camley Anaerobic Digester are presented in Appendix Figure 6.

on we	%VS on we	%ash on TS	pH	Alkalinity (end point pH 5.75)	Intermediate Alkalinity	Alkalinity (end point pH 4.3)	te/Partial (recommended <0.3)	acetic	propanoic	isobutyric	butyric	isovaleric	valeric	TOT as Acetic Equivalent
0.7%	0.3%	63.4%	7.44	2606	1112	3718	0.43	692	369	32	5	62	3	1054
0.7%	0.2%	67.3%	7.75	3249	798	4047	0.25	242	7	8	3	10	7	266
3.7%	2.8%	24.1%	7.24	4796	2096	6891	0.44	199	44	4	9	12	1	252
1.8%	0.8%	53.4%	7.37	4316	966	5281	0.22	9	0	0	0	0	0	9
3.4%	2.4%	28.6%	7.35	8045	1603	9648	0.20	12	3	0	0	2		16
3.0%	2.1%	29.7%	7.29	9595	1682	11277	0.18	5	0	3	0	0	0	7
3.1%	2.2%	28.9%	7.34	9561	1377	10938	0.14	0	0	0	0	0	0	0
3.7%	2.4%	35.1%	7.75	10989	3421	14410	0.31	30	7	18	0	0	0	47
3.9%	2.6%	32.1%	7.73	10841	3341	14182	0.31	29	7	16	0	0	0	45
4.7%	3.2%	32.5%	7.86	17982	1695	19677	0.09	149	11	30	0	0	0	178
5.1%	3.4%	33.3%	7.78	16211	2903	19114	0.18	199	15	25	0	0	0	228
6.6%	3.7%	44.9%	7.75	19742	3903	23645	0.20	158	334	10	4	7	2	443
6.5%	3.7%	42.9%	7.72	20396	3815	24210	0.19	157	280	6	2	5	1	393
6.4%	4.5%	30.6%	7.68	18607	6362	24969	0.34	163	2091	200	6	15	4	2008
6.2%	4.3%	31.4%	7.7	21078	4722	25800	0.22							
6.3%	4.2%	32.8%	7.9	20667	7104	27771	0.34	341	7297	537	16	486	22	6931
8.73%	6.52%	25.27%		17614	4636	22250	0.26	2574	473	47	64	92	14	**3095**
2.9%	1.9%	32.5%	7.25	9904	3731	13635	0.38	2704	247	39	18	45	3	2970
2.4%	1.53%	35.46%	7.72	11496	2669	14165	0.23	1108	16	173	0	42	3	**1265**
3.0%	2.06%	31.18%	7.8	11982	2433	14415	0.20	926	38	70	20	20	0	**1030**

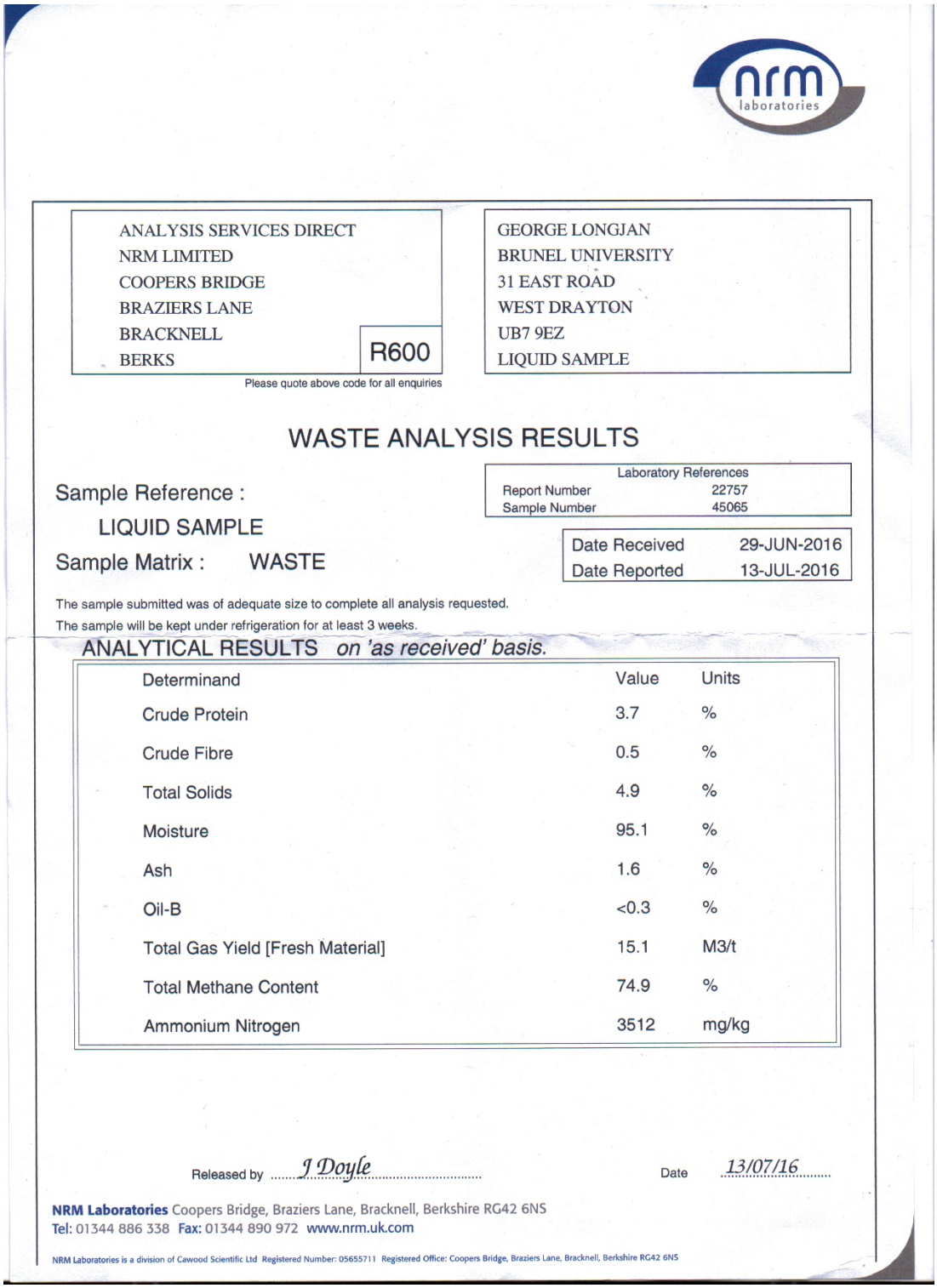
Appendix Figure 6 Camley Anaerobic Digester Digestate analysis.

Appendix Figure 6 cont.

	CATIONS [mg/L]						ANIONS [mg/L]							NPK		
Kind sample	Sodium (Na+)	Calcium (Ca++)	Ammonium (NH4+)	Potassium (K+)	Magnesium (Mg+)	Lithium (Li++)	Fluoride (Fl-)	Chloride (Cl-)	Nitrite (NO2–)	Bromide (Br-)	Nitrate (NO3-)	Phosphate (PO43–)	Sulfate (SO42–)	Soluble inorganic nitrogen [mg N/L]	Soluble inorganic phosphorus [mg P/L]	Soluble inorganic potassium [mg
whole	261	336	629	700	104	0	0	456	0	0	0	88	20	489	29	700
																0
supernatant	367	268	919	893	117	0	0	601	0	26	0	88	17	714	29	893
settled	400	384	1096	931	104	0	0	653	0	33	0	120	15	852	39	931
																0
supernatant	314	304	1026	720	85	0	0	530	0	63	68.7	118	45	814	38	720
settled	458	300	1614	1036	4	0	0	760	0	83	0	105	44.6	1255	34	1036
																0
supernatant	553	241	2188	1230	60		not analysed							1702	0	1230
settled	559	221	2213	1240	57		not analysed							1721	0	1240
																0
supernatant	702	220	2955	1546	42	0	0	1202	0	85	0	176	18	2299	57	1546
settled	673	207	2857	1484	44	0	0	1151	0	29	0	179	14	2222	58	1484
																0
supernatant	890	165	4107	1949	27	0	0	1554	0	98	0	341	0	3194	111	1949
settled	846	177	3899	1852	25	0	0	1490	0	181	0	342	0	3033	112	1852
																0
supernatant	889	0	5010	1797	0	2	0	1429	47	0	0	234	15	3911	76	1797
settled	990	78	5806	2228	2	2	0	1580	47	12	0	271	14	4530	88	2228
																0
supernatant	1320	114	6172	2373	11	2	0	2362	0	0	328	365	0	4874	119	2373
settled	1215	35	5985	2275	18	2	0	2433	0	0	242	415	0	4710	135	2275
																0
whole	1591	94	6226	2351	36	0	0.00	2786	0.00	421	0.00	224	28	4842	73	2351
																0
post spill	1081.9	496.3	5209.15	2117.05	25.8	9.8	0	2037	0	89	0	241	29.3	4052	79	2117
																0
CALTHORPE	609	109	3339	1848	49	0	0	1446	0	37	0	127	0	2597	41	1848
CALTHORPE	592	89	3637	2088	8	0	0	1267	0	41	0	108	39.25	2829	35	2088
CALTHOPRE	683	110	4189	2425	24	5	0	**1401**	**0**	**14**	**0**	**105**	**16.45**	3258	34	2425

Appendix 7: Nutrient Characterisation of Inoculum

The results of the nutrient composition and ammonium nitrogen analysis of the inoculum used in the BMP tests is presented below in Appendix Figure 7.



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BRUNEL UNIVERSITY
31 EAST ROAD
WEST DRAYTON
UB7 9EZ
LIQUID SAMPLE

WASTE ANALYSIS RESULTS

Laboratory References
Report Number 22757
Sample Number 45065

Sample Reference :
LIQUID SAMPLE
Sample Matrix : WASTE

Date Received 29-JUN-2016
Date Reported 13-JUL-2016

The sample submitted was of adequate size to complete all analysis requested.
The sample will be kept under refrigeration for at least 3 weeks.

ANALYTICAL RESULTS *on 'as received' basis.*

Determinand	Value	Units
Crude Protein	3.7	%
Crude Fibre	0.5	%
Total Solids	4.9	%
Moisture	95.1	%
Ash	1.6	%
Oil-B	<0.3	%
Total Gas Yield [Fresh Material]	15.1	M3/t
Total Methane Content	74.9	%
Ammonium Nitrogen	3512	mg/kg

Released by J Doyle Date 13/07/16

NRM Laboratories Coopers Bridge, Braziers Lane, Bracknell, Berkshire RG42 6NS
Tel: 01344 886 338 Fax: 01344 890 972 www.nrm.uk.com

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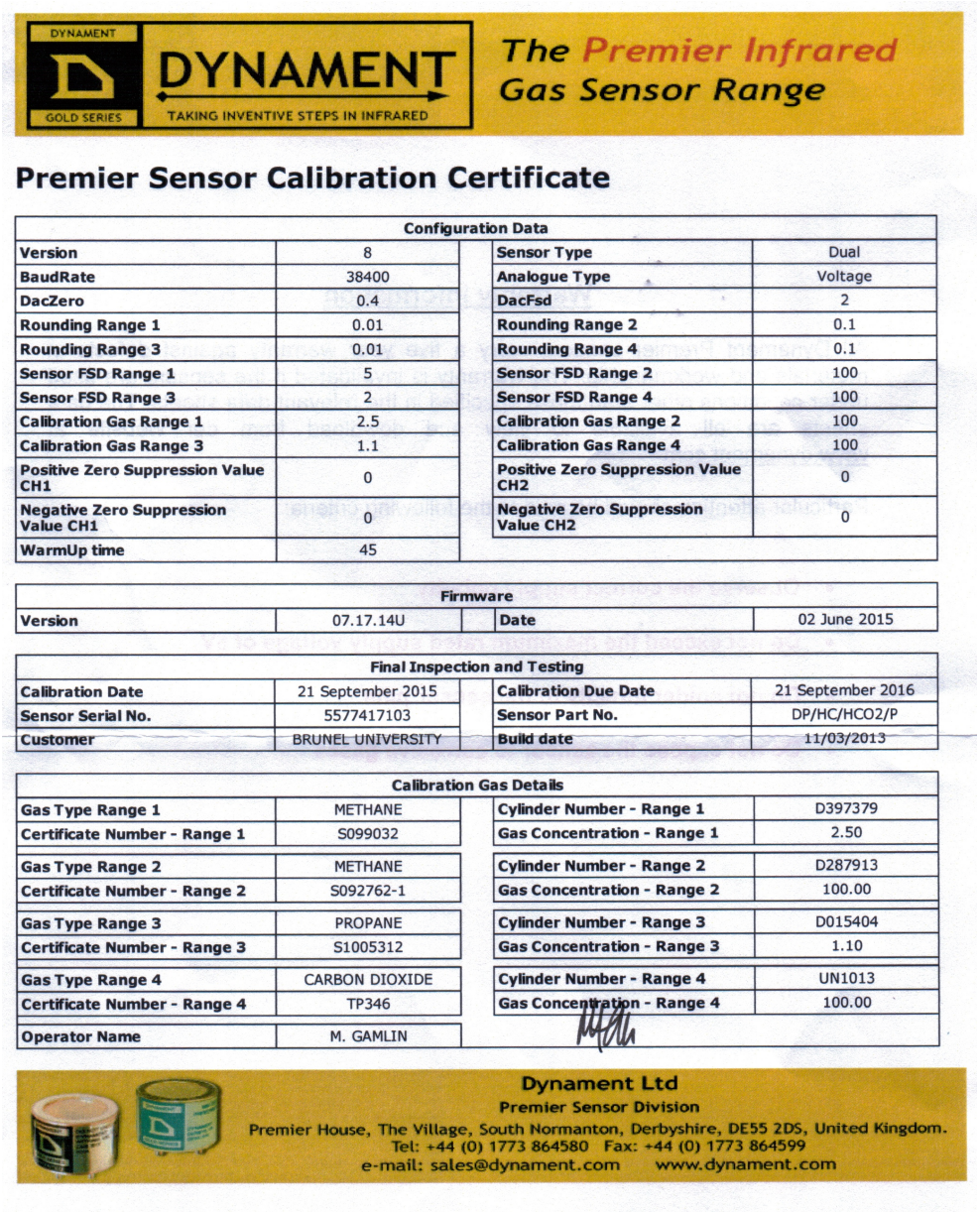
Appendix Figure 7 Inoculum Nutrient and Ammonium Nitrogen Analysis

Appendix 8: Biogas Analyser Calibration Document

The calibration report of the methane and carbon dioxide analyser is presented in Appendix Figure 8.



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The Premier Infrared Gas Sensor Range

Premier Sensor Calibration Certificate

Configuration Data			
Version	8	Sensor Type	Dual
BaudRate	38400	Analogue Type	Voltage
DacZero	0.4	DacFsd	2
Rounding Range 1	0.01	Rounding Range 2	0.1
Rounding Range 3	0.01	Rounding Range 4	0.1
Sensor FSD Range 1	5	Sensor FSD Range 2	100
Sensor FSD Range 3	2	Sensor FSD Range 4	100
Calibration Gas Range 1	2.5	Calibration Gas Range 2	100
Calibration Gas Range 3	1.1	Calibration Gas Range 4	100
Positive Zero Suppression Value CH1	0	Positive Zero Suppression Value CH2	0
Negative Zero Suppression Value CH1	0	Negative Zero Suppression Value CH2	0
WarmUp time	45		

Firmware			
Version	07.17.14U	Date	02 June 2015

Final Inspection and Testing			
Calibration Date	21 September 2015	Calibration Due Date	21 September 2016
Sensor Serial No.	5577417103	Sensor Part No.	DP/HC/HCO2/P
Customer	BRUNEL UNIVERSITY	Build date	11/03/2013

Calibration Gas Details			
Gas Type Range 1	METHANE	Cylinder Number - Range 1	D397379
Certificate Number - Range 1	S099032	Gas Concentration - Range 1	2.50
Gas Type Range 2	METHANE	Cylinder Number - Range 2	D287913
Certificate Number - Range 2	S092762-1	Gas Concentration - Range 2	100.00
Gas Type Range 3	PROPANE	Cylinder Number - Range 3	D015404
Certificate Number - Range 3	S1005312	Gas Concentration - Range 3	1.10
Gas Type Range 4	CARBON DIOXIDE	Cylinder Number - Range 4	UN1013
Certificate Number - Range 4	TP346	Gas Concentration - Range 4	100.00
Operator Name	M. GAMLIN		

Dynament Ltd
Premier Sensor Division
Premier House, The Village, South Normanton, Derbyshire, DE55 2DS, United Kingdom.
Tel: +44 (0) 1773 864580 Fax: +44 (0) 1773 864599
e-mail: sales@dynament.com www.dynament.com

Appendix Figure 8 Calibration report of biogas analyser.

Appendix 9: Variance of Results Data

Appendix Table 1 Variance of waste content of food groups

Food	Variance of Waste content (%)
Yam	24.0
Cassava	8.8
Cocoyam	2.1
Plantain	0.2
Corn	1.9
Egusi	2.0
Beans	0.4
Groundnut	0.4
Ugwu	1.8

Appendix Table 2 Variance of biogas of co-digested substrate

Substrate	Variance of Biogas (%)
YP+WH	1.6
CP+WH	344.5
CoP+WH	171.1
PP+WH	445.2

Appendix Table 3 Variance of biogas of mono-digested substrate

Substrate	Variance of Biogas Yield (%)
YP	847.5
CP	57.7
CoP	111.3
PP	120.4

Appendix 10: Kruskal-Wallis Results

This section presents the results of the various Kruskal-Wallis tests performed in the study.

Appendix Table 4 Kruskal-Wallis results of various food sample waste content

Ranks

	Food Sample	N	Mean Rank
Waste Content (%)	Yam	3	10.67
	Cassava	3	4.33
	Cocoyam	3	12.67
	Plantain	3	20.00
	Corn	3	26.00
	Egusi	3	3.00
	Beans	3	12.00
	Groundnut	3	14.33
	Ugwu	3	23.00
	Total	27	

Test Statistics[a,b]

	Waste Content (%)
Chi-Square	23.450
df	8
Asymp. Sig.	.003

a. Kruskal Wallis Test

b. Grouping Variable: Food Sample

Appendix Table 5 Kruskal-Wallis analysis of results of biogas from co-digested feedstock

Ranks

	Feedstock Type	N	Mean Rank
Biogas (m^3/kg VS)	YP+WH	2	7.50
	CP+WH	2	1.50
	CoP+WH	2	4.75
	PP+WH	2	4.25
	Total	8	

Test Statistics[a,b]

	Biogas (m^3/kg VS)
Chi-Square	6.114
df	3
Asymp. Sig.	.106

a. Kruskal Wallis Test

b. Grouping Variable: Feedstock Type

Appendix Table 6 Kruskal-Wallis analysis of results of biogas from mono digested feedstock

Ranks

	Feedstock Type	N	Mean Rank
Biogas (m^3/kg VS)	YP	2	7.50
	CP	2	1.50
	CoP	2	5.00
	PP	2	4.00
	Total	8	

Test Statistics[a,b]

	Biogas (m^3/kg VS)
Chi-Square	6.167
df	3
Asymp. Sig.	.104

a. Kruskal Wallis Test

b. Grouping Variable: Feedstock Type

Appendix 11: Anaerobic Digestion and Co-Digestion Feedstock Studies

Appendix Table 13 Various AD Feedstock Studies

Energy Crops	Studies
Various Energy Crops	Amon et al., 2007a; Heiermann et al., 2009; Lindorfer et al., 2008; Mayer et al., 2014, Gissen et al., 2014; Barbanti et al., 2014
Maize	Bruni et al., 2010; Amon et al., 2007b; Oslaj and Mursec, 2010; Schittenhelm, 2008; Hinken et al., 2008; Cysneiros et al., 2008
Sugar beets	Cirne et al., 2007; Demirel and Scherer, 2008; Alkaya and Demirer, 2011
Sunflower	Polat et al., 1993
Potato	Kaparaju and Rintala, 2005
Hemp	Kreuger et al., 2011
Grass	Lehtomaki et al., 2008; Yu et al., 2002; Romano et al., 2009
Sorghum	Jerger et al., 1987; Richards et al., 1991; Antonopoulou et al., 2008
Weeds	**Studies**
Water Hyacinth	Moorhead and Nordstedt, 1993; O'Sulllivan et al., 2010; Chuang et al., 2011; Cheng et al., 2010; Ganesh et al. 2005; Geeta et al., 1990; Chanakya et al., 1993; Zhou et al., 2009; Tan et al., 2008; Patil et al. 2011
Channel Grass	Singhal and Rai, 2003
Salvinia	Abbasi et al., 1990
Cabomba	O'Sullivan et al., 2010
Cattail	Hu and Yu, 2006; Yue et al., 2007; Hu et al., 2007
Seaweed	Peu et al., 2011
Common Reed	Riggio et al., 2015
Crop Waste	**Studies**
Crop Residue	Lehtomaki et al. 2008
Corn Stalks	Li et al. 2014
Corn Husk	Owamah and Izinyon, 2015
Corn, sorgos and wheat straw	Yong et al., 2015
Rice Straw	Li et al., 2015b
Tobacco Stalk	Liu et al., 2015
Agricultural Residue	Abouelenien et al., 2014
Animal Waste	**Studies**
Cattle Manure	Akassou et al., 2010; Fang et al., 2011; Dareioti et al., 2010
Pig Manure	Riano et al., 2011
Poultry Litter	Sharma et al., 2013; Li et al., 2014; Wang et al., 2014; Khoufi et al., 2015
Animal By-Products	**Studies**
Solid Slaughterhouse waste	Pages-Diaz et al., 2014; Bayr et al., 2014
Fish Waste	Serrano et al., 2013
Food Wastes	**Studies**
Food waste	Kim and Oh, 2011; Rajagopal et al., 2013; Brown and Li, 2013; Shen et al., 2013; Wang et al., 2014; Liao et al., 2014; Zhang et al., 2016

Fruit and vegetable waste	Fonoll et al., 2015
Sardine oil	Ferreira et al., 2012
Coffee grounds	Qiao et al., 2013
Industrial Waste	**Studies**
Winery Wastewater	Riano et al., 2011
Fish and Strawberry Waste	Serrano et al., 2013
Orange Peel Waste	Martin et al., 2013
Petrochemical waste	Siddique et al., 2014; Siddique et al., 2015
Pear Waste	Dias et al., 2014
Soy bean processing waste	Zhu et al., 2014
Potato Processing Waste	Kaparju and Rintala, 2005
Sugar beet by product	Fang et al., 2011; Aboudi et al., 2015
Potato pulp	Bayr et al., 2014
Olive mill wastewater	Goberna et al., 2010; Dareioti et al., 2010
Distillery Wastewater	Akassou et al., 2010
Distillers Grains	Wang et al., 2012
Glycerine	Castrillon et al., 2013; Razaviarani and Buchanan, 2015
Than Sillage	Sharma et al., 2013
Paper Waste	Kim and Oh, 2011
Scrap iron	Zhang et al., 2014
Algae	**Studies**
Algae	Golueke and Oswald, 1957; Ras et al., 2011; Sarker et al., 2014; Ward et al., 2014
Microalgae	Gonzalez-Fernandez, 2011; Ajeej et al., 2015; Collet et al., 2011
Sewage	**Studies**
Sewage Sludge	Fernandez et al. 2008; Fonoll et al., 2015; Zhang et al., 2016; Zhen et al., 2015
Municipal Sludge	Borowski and Weatherly, 2013; Ajeej et al., 2015; Li et al., 2015a; Razaviarani and Buchanan, 2015
Brown Water	Rajagopal et al., 2013

Appendix Table 14 Co-substrates and their studies.

Cattle Manure with:	Study
Corn Stalks	Li et al. 2015b
Crop Residue	Lehtomaki et al. 2008
Distillery Wastewater	Akassou et al., 2010
Olive Mill Wastewater	Goberna et al., 2010; Dareioti et al., 2010
Sugar Beet By-products	Fang et al., 2011
Crude Glycerine	Castrillon et al., 2013
Algae	Sarker et al., 2014
Pig Manure with:	**Study**
Potato Waste	Kaparju and Rintala, 2005
Microalgae	Gonzalez-Fernandez, 2011
Winery Wastewater	Riano et al., 2011
Waste Sardine oil	Ferreira et al., 2012
Seaweed	Peu et al., 2011
Poultry Litter with:	**Study**
Cow Manure	Miah et al., 2015
Olive mill wastewater	Khoufi et al., 2015
Municipal Sewage Sludge	Borowski and Weatherly, 2013
Thin Silage	Sharma et al., 2013

Agricultural Waste	Abouelenien et al., 2014
Corn Stover	Li et al., 2014
Food Waste	Wang et al., 2014
Sewage Sludge with:	**Study**
Food Waste	Zhang et al., 2016
Microalgae and waste paper	Ajeej et al., 2015
Fats, oil and grease	Li et al., 2015a
Aquatic plants	Zhen et al., 2015
Biodiesel waste glycerine	Razaviarani and Buchanan, 2015
Scrap iron	Zhang et al., 2014
Food Waste with:	**Study**
MSW leachate	Zhang et al., 2015
Land fill leachate	Liao et al., 2014
Maize husk	Owamah and Izinyon, 2015
Wheat Straw	Yong et al., 2015
Distiller grain	Wang et al., 2012
Brown water	Rajagopal et al., 2013
Green Waste	Brown and Li, 2013
Paper waste	Kim and Oh, 2011
Fruit and veg waste	Shen et al., 2013
Industrial based waste	**Study**
Slaughterhouse Waste with Cow, pig and horse manure	Pages-Diaz et al., 2014
Slaughterhouse Waste with Fruit & veg residue & straw	Pages-Diaz et al., 2014
Fish waste with Strawberry Waste	Serrano et al., 2013
Orange peel waste with Biodiesel waste glycerol	Martin et al., 2013
Petrochemical waste with Activated manure	Siddique et al., 2015
Petrochemical wastewater with Cow manure	Siddique et al., 2014
Pear waste with Cow manure	Dias et al., 2014
Soy bean processing waste with Hay	Zhu et al., 2014
Industrial waste with Cow manure	Nordell et al., 2016
Coffee grounds with Waste activated sludge	Qiao et al., 2013
Sugar beet by product with Pig manure	Aboudi et al., 2015
Potato pulp with Slaughterhouse waste	Bayr et al., 2014
Plant based co-digestion	**Study**
Tobacco and wheat stalk with Pig manure	Liu et al., 2015
Tobacco and wheat stalk with Cow manure	Liu et al., 2015
Tobacco and rape stalk with Pig manure	Liu et al., 2015
Tobacco and rape stalk with Cow manure	Liu et al., 2015
Rice straw with Cow manure	Li et al., 2014b
Common reed with Cheese whey	Riggio et al., 2015