School of Civil Engineering, Surveying and Construction

ANAEROBIC DIGESTION OF ENERGY CROP (CASSAVA)

Nathaniel O. Sawyerr

Submitted in fulfilment of the academic requirements for the degree of *Doctor of Philosophy in Environmental Engineering, College of Agriculture, Engineering and Science*

University of KwaZulu-Natal, Durban

2019

Supervisor: Prof. Cristina Trois

Co-supervisor. Prof. Tilahun Workneh

PREFACE

The research presented in this thesis was carried out under the supervision of Prof. Cristina Trois of the School of Civil Engineering, Surveying and Construction, University of KwaZulu-Natal, Durban, South Africa. This thesis is comprised of a set of discrete research papers and has been compiled in accordance with The Guidelines for the Writing of a PhD, prepared by the College of Agriculture, Engineering and Science at the University of KwaZulu-Natal, Durban and represents work written by Nathaniel Sawyerr, unless otherwise stated in the text.

SUPERVISOR AND CO-SUPERVISORS' AGREEMENT

As the candidate's supervisor and co-supervisors, we have approved the submission of this thesis.

…………………………… ………………………

Professor C Trois Date
Research Supervisor

………………………….. ………………………

Professor T S Workneh Date
Research Co-supervisor

DECLARATION 1: PLAGIARISM

I, Nathaniel Sawyerr declare that:

i. The research reported in this thesis, except where otherwise indicated, is my original research.
ii. This thesis has not been submitted before for any degree or examination to any other university.
iii. This thesis does not contain any other person's pictures, data, and graphs or other information, unless specifically acknowledged as being sourced from other persons.
iv. This thesis does not contain any other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written, but the general information accredited to them has been referenced;
    b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.
v. Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated in detail which part of the publication was actually written by myself alone and have fully referenced such publications.
vi. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

…………………………..	……………………………	…………………..
Name	Signature	Date

DECLARATION 2: PUBLICATIONS

Details of contribution to publications that form part and/or include research presented in this thesis (this includes publications in preparation, submitted, in press, and published and giving details of the contributions of each author to the experimental work and writing of each publication).

PUBLICATIONS FROM THIS THESIS

Publication 1

Sawyerr, N., Trois, C., Workneh, T. and Okudoh, V., 2018, An Overview of biogas production: fundamentals, applications and future research *(Literature Review)*. *International Journal of Energy Economics and Policy* (see copy in APPENDIX P1)

Publication 2

Sawyerr, N., Trois, C., and Workneh., 2018, Identification and Characterization of Potential Feedstock for Biogas Production in South Africa. *Journal of Ecological Engineering* (see copy in APPENDIX P2)

Publication 3

Sawyerr, N., Trois, C., Workneh, T. and Okudoh, V., Co-Digestion of Animal Manure and Cassava Peel for Biogas Production in South Africa. *Proceedings of the 9th International Conference on Advances in Science, Engineering, Technology and Waste Management (ASETWM-17), Nov. 27-28, 2017, Parys, South Africa*. (see copy in APPENDIX P3)

Publication 4

Sawyerr. N, Trois. C, Workneh. T. and Okudoh, V., 2018 Comparison and Kinetic Modelling of Biogas Production from Whole and Peeled Cassava Tubers at a Mesophilic Temperature. *International Journal of Mechanical Engineering and Technology* (see copy in APPENDIX P4)

Publication 5

Sawyerr. N, Trois. C, Workneh. T: Optimization of Biogas Yield through co-digestion of Cassava Biomass and Vegetable & Fruits waste at Mesophilic Temperatures

[*International Journal of Renewable Energy Research, Accepted*] (see copy in APPENDIX P5)

Publication 6

Sawyerr. N, Trois. C, Workneh. T: Designing of Small-Scale Biogas digester for co-digestion of Cassava and Other biomass [*In Preparation*]

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the following:

- My supervisor, Prof. Christina Trois, and co-supervisors, Prof T.S. Workneh and Dr Vincent Okudoh for their continued guidance and support.
- Mbuso Cele and the Pietermaritzburg mechanical workshop team for their assistance in building the digester.
- My family, more especially Oluwatosin Akinosun, for their unconditional love and unending motivation throughout the entire duration of the PhD programme.
- My fellow friends and brothers, Mr Olubayo Babatunde, and Mr Oluwaseun Oyebode for the support and encouragement during difficult times.

DEDICATION

To God and the Sawyerr family

ABSTRACT

Global energy demand is on the rise due to continuous increases in population, economic growth, and energy usage. Methane production through anaerobic digestion of organic materials provides a resourceful carrier of renewable energy, as methane can be used instead of fossil fuels for both heat and power generation and also as vehicle fuel, thus cutting down the emissions of greenhouse gases and hence contribution in the slowing down climate change. Several studies have been done on biogas, but in South Africa, these are biased towards industrial wastewater. Therefore, there is need to explore other alternatives for biogas generation. Furthermore, the sustainability of anaerobic digestion processes depends on the availability and the identification of the optimal substrate.

The use of cassava in South Africa provides a great potential for the production of bioenergy especially biogas, due to its suitable chemical composition. Cassava co-digested with other feedstock could be an alternative substrate for various communities for the production of biogas in South Africa. Since cassava is yet to be listed as a staple food crop in South Arica, its peels and other by-products from its processing can be suitable for renewable energy production for small medium enterprises (SMEs).

This study's overall objective was that of establishing the suitability of cassava tubers as an alternative source of biomass feedstock for biogas production in South Africa. The specific objectives of the study were: 1) Comparing the yield and rate of biogas production of cassava peels inoculated with cattle manure using a batch digester under anaerobic digestion conditions addressed in chapter four and five of the thesis; 2) Investigate the biogas yield and rate of different co-digestion ratios of cassava with vegetable and fruit waste using batch digestion under anaerobic digestion conditions presented in chapter six; 3) Optimize the production of biogas through process optimization by maintaining the optimum temperature during fermentation and compare inexperiments subjected to different treatment or treatment combinations and, 4) While chapter seven addresses the objective of using the experimental results to design an upscale system using baseline data information from experiment.

Several feedstocks (i.e. cassava tuber, cassava peels, vegetable and fruit waste and cattle manure) were identified and analysed using the American Standard Methods for

Examination of Water and Wastewater (ASTM). Cassava was selected as it has several advantages compared to other crops, including the ability to grow on degraded land and where soil fertility is low. It also has the highest yield of carbohydrate per hectare (4.742 kg/carb) apart from sugarcane and sugar beet, which makes it suitable for bioenergy (biogas) generation.

In the first instance, a batch experiment of were cassava peels were digested anaerobically with and without cattle manure to determine whether cassava peels (CP) in combination with cattle manure (CM) at different ratios shows better biogas yield. The following ratio combinations of mixture were used 100:0, 0:100, 80:20 and 20:80 (CM:CP). A theoretical methane production was conducted using elemental composition and the results were compared with the experimental ones. The test of biogas yield was conducted using an anaerobic digester of 600 ml at mesophilic (35 ± 1 °C) temperature.

In the second experiment a 50 litres anaerobic digester was used to investigate the biogas yield of peeled cassava tuber compared to unpeeled cassava tuber that yield biogas of 635.23 L/kg VS and 460.41 L/kg VS respectively. This was based on the finding of the first experiments of biogas yield from cassava peels. The biogas yield with and without inoculum was measured and the biogas yield were modelled using two different models namely modified Gompertz and cone model.

Finally, in parallel with the previous batch experiments another set of batch experiments were carried out under anaerobic conditions at mesophilic (35 ± 1 °C) temperature in a 600 ml digester, this experiments was conducted by co-digesting cassava (CB) with vegetable and fruit waste (CB:VF) at different ratios (100:0, 60:40, 40:60 and 50:50). The cumulative biogas yield were modelled for kinetics using modified Gompertz model.

Based on the results obtained from the experimental study cassava co-digested with vegetable and fruits at a ratio of 40:60 which was found to produce the maximum yield, a mathematical design (upscale system) was designed. This designed biogas plant could be located in several communities especially those close to the landfills to reduce the cost of transportation from source.

The study's results revealed that:

- co-digestion influenced biogas production and methane yield. The final cumulative methane yields by the co-digestion of CM and CP at the CM:CP mixing ratios of 80:20 and 20:80 were 738.76 mL and 838.70 mL respectively. The corresponding average daily methane yields were 18.42 mL/day and 20.97 mL/day. This indicates that CP enhanced the production of methane in the co-digestion process with the 20:80 CM:CP ratio.

- the feedstock of peeled cassava with inoculum, produced 28.75% more biogas yield when compared to peeled cassava without inoculum. This results highlights the important of inoculum in the anaerobic digester.

- peeling the cassava tuber increase the biogas yield by 38% compared to the unpeeled tuber

- cassava biomass co-digested with vegetable and fruit waste increased the methane yield compared to the mono-digestion with the highest methane production was achieved from the co-digestion of cassava biomass with vegetable & fruit waste at 40:60 ratio (CB: VF)

Although several challenges hampering the smooth implementation of biogas generation in South Africa, this study concludes that cassava (peeled and unpeeled) co-digested with fruit and vegetables waste has potential to generate biogas thereby presenting a substantial opportunity to promote bioenergy production from cassava considering in many rural areas the needs for fuel and electricity are not satisfied fully. Finally, cassava anaerobic digestion facility at different scales could enhance additional benefits like the integration of nutrients and residual carbon into the land as fertilizer.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1:
INTRODUCTION

1.1 BACKGROUND

The energy demand of the world is continually increasing due to the continuous increase in the world's population, economic growth, and energy usage (Hasan et al., 2012). The global population will likely increase in the next 40 years by 2.5 billion, well above the current population range of 6.7 to 9.2 billion (Okudoh et al., 2014). The projection indicates that in developing countries, population will rise from 5.4 billion in 2007 to 7.9 billion in 2050 (Hiv/Aids Junpo and Organization, 2007). Due to the increase in population, both developed and developing countries are facing mainly issues surrounding the present and future energy security. Research has shown that increase in the energy demand globally is intimately tied to two important trends. First, the requirement of energy per person has grown since the 1960s (Ritchie and Roser, 2014), and second, there is a continuous growth of population energy consumers since 2001 (Dekanić et al., 2002). Considering a prediction that the earth's population would have increased to around 9 billion people by 2050 (Béné et al., 2015), there is an ongoing effort towards increasing the global supply of energy to meet growing demands.

The most common source of energy is fossil fuel (Council, 2016). Fossil fuel is considered a non-renewable source of energy because it cannot be replenished at the same time as its consumption rate. From the 19th century onwards, coal has been the heavily used fossil fuel (Campbell and Wöstmann, 2013). Coal is widely used for fuel and about 36% of the world electricity is produced from coal. With the development of different technologies, which has improved the conversion efficiencies, the potential of oil became apparent, and thus, making oil and gas a substitute to coal. Since then, the world has been heavily reliant on fossil fuels (Kuiper et al., 2007). However, fossil fuels as an energy resource are globally believed and accepted to be finite and with their discovery and processing regarded as too costly in monetary and energy terms to be utilizable (Khamis and Papenbrock, 2014). Moreover, the exploration and consumption of fossil fuels have been found to have a significant contribution to increased rate of carbon emissions, and this has, in turn, been directly linked to global warming and climate change (Judkins et al., 1993). In the light of these drawbacks, renewable energy sources are being explored with the aim of having a viable alternative to existing conventional energy sources like fossil fuels.

Renewable energy sources offer an opportunity to solving present and future energy problems. Examples of renewable energy sources include solar, wind, nuclear, hydropower, geothermal, and biomass. The major challenge with most renewable energy sources however is that their availability is often characterised by high variability (Beaudin et al., 2010), thus making them to be only usable when the resources are available. Solar and wind energy, for example are dependent on highly variable nonlinear local and regional weather patterns. Although nuclear energy is known for a high energy generation potential and a relatively little contribution to global warming (Linnerud et al., 2011), Uranium, which is the raw material used for generating nuclear energy, is considered a naturally unstable element and therefore limited in availability (Züttel et al., 2011). In addition, nuclear plants, if not managed within regulatory standards, are prone to accidents which could have devastating effects on both human beings and the nature. Nuclear energy is also known for generating extremely dangerous radioactive wastes. Water availability remains a major issue in many countries of the world and this continues to impact the adoption of hydro-energy (hydropower plants) (Branche, 2017), especially in water-scarce regions. Another major challenge with renewable energy sources is that, harnessing their full potential, even when they are available in abundant quantity, could be challenging or sometimes impossible. For instance, solar energy is received by the earth is about 11 000 times the energy that the global population needs in a year (Kuiper et al., 2007, Kannan and Vakeesan, 2016). However, due to high dispersion, only a small percentage is recovered for consumption purposes. Geothermal energy is location specific and expensive, and may result in the migration of potential greenhouse gases and toxic elements below the Earth to the surface and into the atmosphere (Hoegh-Guldberg and Bruno, 2010). Consequently, the identification of sustainable renewable energy sources that will produce a large volume of energy like coal has been a major challenge across the globe.

Biomass energy is considered as a sustainable renewable energy source (Srirangan et al., 2012). This is because biomass is organic material that comes from plants and animals which contains stored energy from the sun and is always available and producible.

Biomass energy is typically harnessed by anaerobically digesting organic degradable material for production of gas often referred to as biogas (Nekhubvi and Tinarwo, 2017). In the past, anaerobic digestion of organic degradable material as a source of biogas was used mainly for degradation of waste materials or toxic compounds (Appels et al., 2011). However, in recent times, production of biogas from energy crops is becoming increasingly popular (Weiland, 2010, Weiland, 2003). Since the promulgation of the Renewable Energy Sources Act (REA) in 2000 in Germany, the interest in anaerobic fermentation of energy crops as a source of electrical energy has increased significantly, coupled with support from relevant stakeholders. In 2002, the REA supported the production of electricity from biogas through a refund of approximately 0.1023 Euro per kWh (Okudoh et al., 2014).

On the continent of Africa, there is a significant gap between energy production and consumption rates as cities struggle to meet the energy demand of their inhabitants (Maltsoglou et al., 2013). Many African countries spend a large amount of their budget on the importation of energy (Winkler, 2005, Galarraga et al., 2011). These funds however could be used for development of other areas of the economy. Lack of a constant supply of energy remains one of the factors that critically affects the development of industries such as agriculture, manufacturing, mining and tourism on the continent. As a result, there is an urgent need to develop renewable energy resources, particularly biofuels and biogas, which is considered a non-conventional, promising renewable energy carrier (Adelekan and Bamgboye, 2009). According to Van Zyl et al. (2011), in South Africa, about 20% of the total land mass of 120 million hectares (Mha) is being used for biomass production. It is hoped that this will bring about the reduction of dependence on fossil fuels, mitigate the negative social and environmental impacts on the lives of the people and the successful optimization of the conversion of biomass to energy (Change, 2007). Bio-fuels and biogas (considered to be the low carbon fuel sources) offer the best opportunities to the rural communities in African countries to meet their energy demand. The advantages of biomass energy over other renewable energy sources include the following:

- Availability of raw material as waste is always generated.

- Reduction of waste as organic agricultural waste and municipal solid waste (MSW) could be used for energy production.
- the improvement of environmental quality through CO_2 emission reduction (Soccol et al., 2011).
- Reduction of waste disposal to landfill as organic waste in digested for generation of valuable energy.
- Reduction in the cost and effort required for grid extension to remote areas as biomass energy systems offers a platform for distributed energy generation which in turn provides an opportunity to supply electricity to off-grid rural communities.
- Allows for peak saving rather than the use of gas generators.
- Reduces political resource use conflicts related to gas installations/ pipelines.

The disadvantages of biomass energy include the following:

- Lack of agricultural wastes when the basic crops are no longer grown.
- Additional work required for harvesting.

1.2 RATIONALE AND JUSTIFICATION OF STUDY

In South Africa, coal has been the main source of energy. It provides approximately 74.8% of the energy in the country (Musango et al., 2011). The other sources of energy supply in South Africa include oil, gas, nuclear power, hydropower and renewable sources such as wind, solar, biomass and wave power. The percentage distribution of energy supply in South Africa is shown in Figure 1-1.

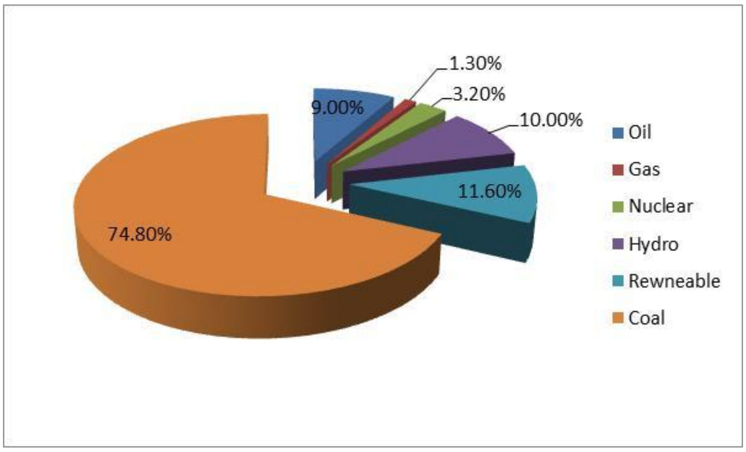


Figure 1-1: Percentage distribution of energy to total primary energy supply in South Africa (Musango et al., 2011).

In 2002, about 77% of South African energy needs were provided by coal and this has remained unchanged over the years (Solangi et al., 2011). The coal industry feeds various local industries, about 53% of which goes to the generation of electricity. Research has shown that that about 53 billion tonnes of coal reserves are left, which will last for only a few decades more, going by the current production rate (Akinyemi et al., 2012). The identification of suitable alternative energy sources to coal and introduction of a variety of energy mix is thus critical to bridge the gap between energy production and rising demand.

1.3 POTENTIAL AND JUSTIFICATION OF THE USE OF CASSAVA AS AN ENERGY CROP

Cassava is a valuable crop in many African countries (Figure 1-2). Cassava is a starchy root crop, with a starch range of 20–35% fresh and 80.6% dry (Wang, 2002, Jansson et al., 2009). It is being cultivated in many countries in Africa, America and Asia. According to Haggblade et al. (2012), cassava is the second most important staple food in African diets. However, it is still a minor plant in South Africa (Okudoh et al., 2014). The use of cassava provides great potential for the production of bioenergy, especially biogas, due to its chemical composition. A report by the Forum for Agricultural Research in Africa (Diaz-Chavez et al., 2010), indicates that there are thousands of acres of degraded and unused land in Africa, which can be used for cultivating crops such as cassava for the purpose of bio-fuels production on a larger scale (Winchester and Reilly, 2015).

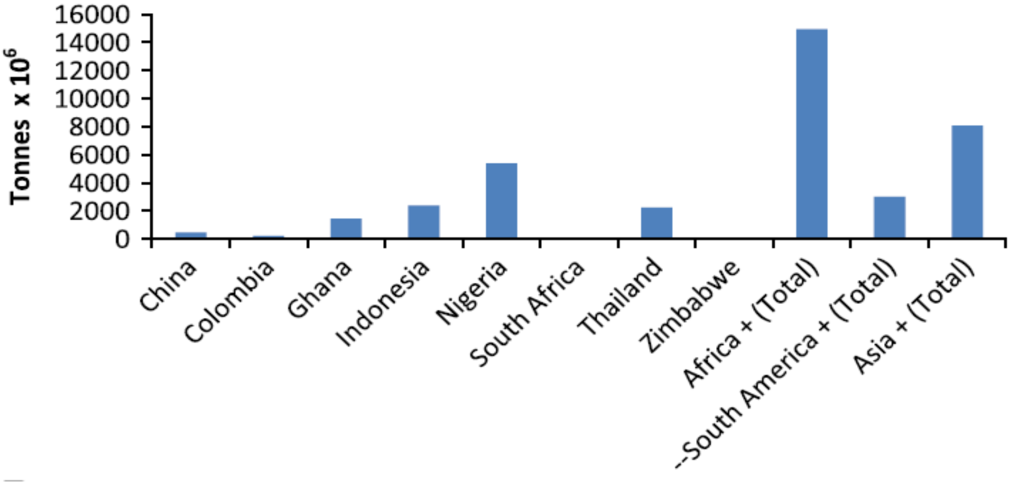


Figure 1-2: Global cassava production for 2012 (Okudoh et al., 2014, Faostat, 2018).

Cassava has several advantages compared to other crops. This is because it can grow in areas where the land has been degraded and where there is low soil fertility. Cassava usually survives and produces better harvests in locations where maize and other energy crops will not grow or yield bountifully (Hillocks et al., 2002, Spencer and Ezedinma, 2017). It has the highest yield of carbohydrates (4.742 kg/carb) per hectare besides sugarcane and sugar beet (Okudoh et al., 2014). According to Gerbens-Leenes et al. (2009), cassava has a low water footprint of 21 m^3/GJ compared to other crops. It is drought tolerant and can survive in extreme weather, climatic conditions and soil with low nutrients. It also yields well to irrigation or in regions with higher rainfall (Spencer and Ezedinma, 2017, Okudoh et al., 2014). For this reason, it is gaining considerable attention in other countries, for example Nigeria, for the production of bioenergy (Jansson et al., 2009), specifically, biogas production (Ezekoye, 2008). Biomass is considered the best source of renewable energy (biogas) and the gas can be used for heating, can be used as fuel and as a natural gas, and can also be converted to electricity. Biogas production from cassava biomass is a biochemical process that takes places through an anaerobic food chain that involves mainly prokaryotes. Biogas production involves various types of feedstock. The quality and yield of the biogas produced depend on the feedstock composition (Lim et al., 2012).

Several developing and developed countries are faced with a range of problems, of which energy security is one (Chu and Majumdar, 2012). The African continent is characterised by a huge gap between energy production and consumption profiles (Wu et al., 2012). The main issue is that most of the energy produced in Africa is from fossil fuel. These fossil fuels have had so much impact on global warming, therefore the need to look for bioenergy production from agricultural crop biomass or residues.

Studies done on biogas in South Africa are biased toward industrial wastewaters (Yenigün and Demirel, 2013). This has created the need to research on energy crops such as fodder beets and cassava. In recent years energy crops such as fodder and cassava has gained momentum in research focus for both food and non-food application (Carter et al., 1993, Oladeebo and Oyetunde, 2013). However, in South Africa, cassava is not a well-known crop. This is because cassava is not yet considered a staple food in the country (Godfray et al., 2010). For this reason, limited information are available on biogas studies from cassava biomass and other energy crops (Hall et al., 1982). The non-consideration of cassava as a staple food in South Africa however provides an opportunity to explore its energy potential in biogas production as it offers no negative impacts on food security. The ability of the crop to grow under varying extreme conditions implies that its growth and survival is guaranteed in South Africa, if adequate resources are invested.

Existing studies on cassava, mainly reported in the 1980's have only focused on the production of starch from cassava (Morgan and Choct, 2016). The aim of this study is therefore to evaluate the potential of cassava biomass in biogas production through anaerobic digestion. To achieve this aim, the effects of the key factors (pH, nutrients, temperature, flow rate of feed (loading rate), retention time and type of feedstock) on biogas yield (methane gas production) are investigated. Because the cultivation of cassava in South Africa is at a very low scale, this research was not limited to cassava as the sole substrate. This study thus explores the biogas production potential of different co-digestion scenarios. The co-digestion of cassava with other feedstock could be an alternative substrate for biogas production in South Africa. Since cassava is yet to be listed as a staple food crop in South Arica, cassava, its peels and other by-products from it processing can be suitable for energy production.

This study thus explores the use of different cassava parts for biogas production using anaerobic digestion.

1.4 OVERALL AND SPECIFIC OBJECTIVES

The broad objective of this study is to investigate the suitability of cassava as an alternative source of biomass feedstock for biogas production in South Africa.

The specific objectives of the study are as follows:

1) To compare the yield and rate of biogas production of cassava peels inoculated with cattle manure under anaerobic digestion;
2) To investigate the biogas yield and rate of different co-digestion ratio of cassava with vegetable and fruits waste using batch digestion at anaerobic digestion;
3) To optimize the production of biogas through process optimization by maintaining the optimum temperature during fermentation;

4) To compare experimental and predicated biogas yields and develop a mathematical model based on the yields obtained; and
5) To design an upscale system using experimental baseline data information.

1.5 RESEARCH APPROACH AND METHODOLGY

The methodological approach to achieving the outlined objectives of this study requires large scale and small-scale experiments under anaerobic digestion. This enables the establishment of the optimum factors and co-digestion of cassava tuber with vegetable and fruit waste with cattle manure (as inoculum) at different ratio under various conditions in a batch system. The data obtained from the different substrates at different ratios were captured as they provide critical information necessary for the simulation and design of upscale biogas digester. A brief methodological framework approach used in this study is summarized in Figure 1-3 starting from feedstock identification (step 1) till designing a small scale digester (step 5) for five (5) families with each family having 8 people:

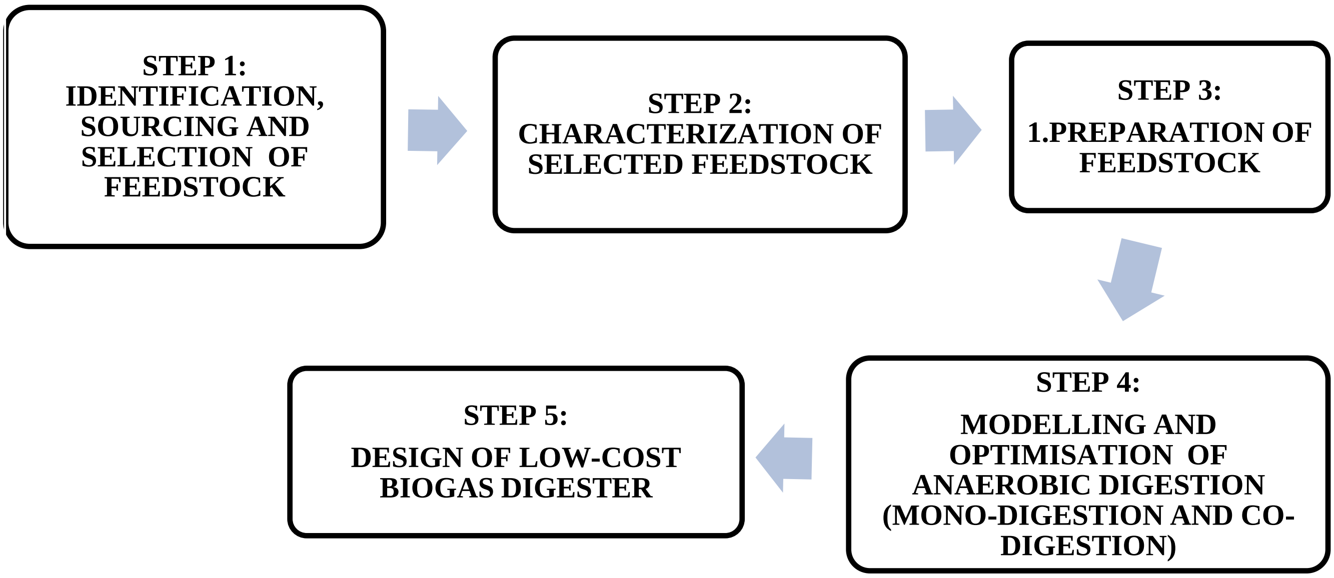


Figure 1-3: Methodological framework of the study

1.6 RESEARCH SIGNIFICANCE AND CONTRIBUTION TO KNOWLEDGE

This research focuses on the current gap between biogas production from wastewater and energy crop. The huge gap between energy supply and demand coupled with the drawbacks of coal and other alternative energy sources give rise to the need for alternative energy generation from drought tolerant plant materials such as cassava. However, much research attention has been given to biogas production from industrial wastewaters in South Africa (Stafford et al., 2013, Demirel and Scherer, 2008). However, biogas production from biomass, especially energy crops have received little or no attention (Okudoh et al., 2014). Different varieties of plant in sub-Saharan Africa, due to their rich organic content, could serve as potential input material in anaerobic fermentation and production of biogas. Energy crops such as cassava have been identified as the major crop for biogas production since they are also drought tolerant plants that can give good yield in South Africa as well as elsewhere in the regions. This research explores cassava, as there is a paucity of research on cassava biomass and other energy crops. This study will contribute in establishing an appropriate way for biogas quantification regarding the use of unpeeled cassava tuber (UCT) and peeled cassava tuber (PCT). Additionally, this study will contribute to knowledge by providing information on the suitable feedstock required for an optimum biogas yield. To this end, a combination of three kinetic models is employed to establish a suitable feedstock for biogas production between UCT and PCT. The development of an innovative conceptual design based on the experiments will serve as guide the construction of small-scale biogas plants which could assist in bridging the gap between energy supply and demand.

1.7 THESIS STRUCTURE

This thesis follows the structure of an “Articles format Thesis”, which will consist of seven chapters. Four main chapters (3, 4, 5 and 6) are a reproduction of original research articles. Chapter 4 has been presented as a conference proceeding, chapters 2, 5 and 6 has been published while 3 is under review. Chapter 8 is an overall conclusion and recommendation. This thesis is therefore organized as follows (Figure 1-4):

Chapter 1 provides an introduction of the thesis, background information of the research and the motivation for this research. The aim and objectives of the research are outlined in this chapter.

Chapter 2 provides a comprehensive literature review focusing on the biogas process extending the possibilities of conversion biomass into biogas from different biomass and the current gap to be filled in order to produce biomass (cassava and vegetable & fruits) based biogas.

Chapter 3 outlines the identification and characterization of potential feedstock for biogas production through anaerobic digestion, including the theoretical review into the biogas yield using substrates elemental composition.

Chapter 4 presents a comparison of mono-digestion and co-digestion of animal manure and cassava peel for biogas production in South Africa under anaerobic digestion, using bench batch experiment.

Chapter 5 focuses on the comparison and kinetic modelling of biogas production through anaerobic digestion of whole and peeled cassava tubers at mesophilic temperature using small scale batch experiment. It also presents the effect of presence of inoculum in the anaerobic digestion of unpeeled and peeled cassava on the biogas yield and rate.

Chapter 6 presents the results of biogas yield through co-digestion of cassava biomass and vegetable & fruits waste. The optimum biogas yield through co-digestion ratio change at mesophilic temperature (37 °C) was compared.

Chapter 7 presents the design of a low-cost biogas digester based on the optimum production obtained from the bench and laboratory results chapter 4, 5, and 6. This will enable the fabrication of the digester with the design specifications.

Chapter 8 summarizes the main research findings and presents the conclusions and recommendation for future research work.

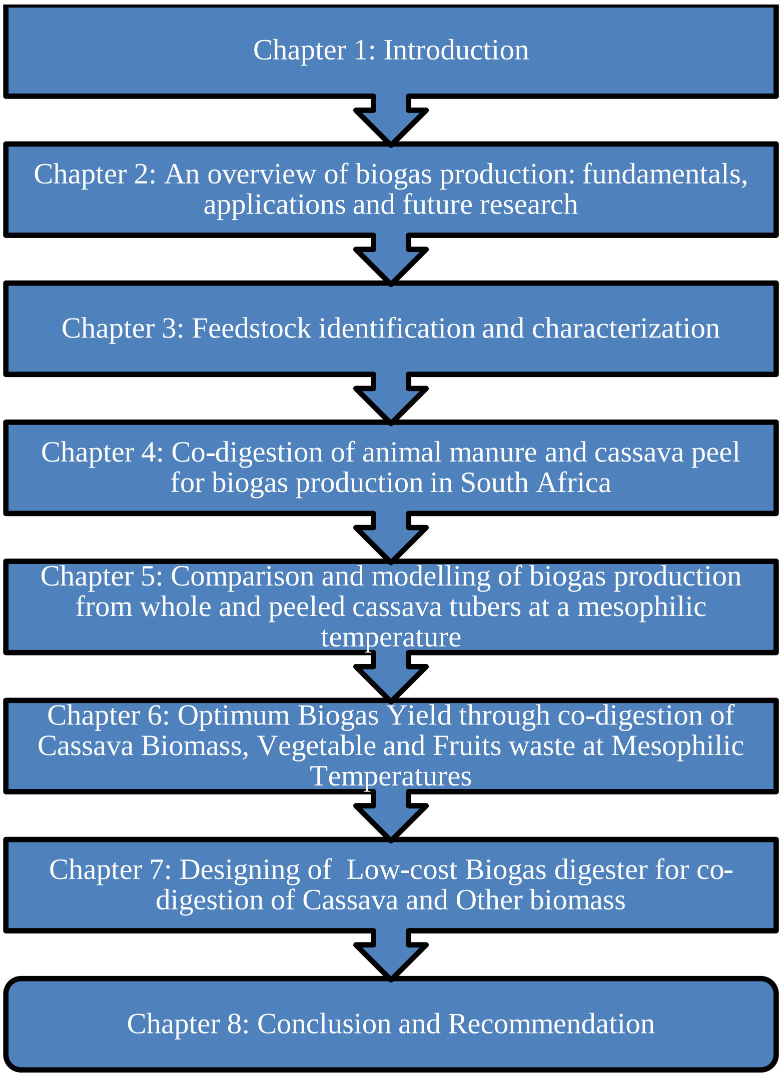


Figure 1-4: Framework of the thesis outline

CHAPTER 2:

AN OVERVIEW OF BIOGAS PRODUCTION: FUNDAMENTALS, APPLICATIONS AND FUTURE RESEARCH – A REVIEW

Nathaniel Sawyerr[1*], Cristina Trois[2], Tilahun Workneh[3], Vincent Okudoh[4]

[1,2]Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

*e-mail: sawyerrnathaniel@gmail.com

e-mail: trois@ukzn.ac.za

[3]Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

e-mail: seyoum@ukzn.ac.za

[4]Department of Biotechnology and Consumer Sciences, Cape Peninsula University of Technology, Cape Town Campus, South Africa.

e-mail: okudohv@cput.ac.za

PREAMBLE

This chapter is written in the form of a research article published in *International Journal of Energy Economics and Policy*, no major changes were made. Only minor changes were made to improve the readability. This chapter is a review paper which presents a comprehensive analysis of anaerobic digestion inclusive of the advantages and disadvantages. Various studies conducted on anaerobic digestion are presented in this chapter and lastly this review highlights the current gaps to be filled in this field. The copy of the original published article is in Appendix P1 as indicated in the declaration section.

https://doi.org/10.32479/ijeep.7375

Received 12 November 2018; Accepted 07 February 2019; View online at International Journal of Energy Economics and Policy (www.econjournals.com)

ABSTRACT

Due to the increase in population, both developed and developing countries are facing mainly issues surrounding the future energy security and a better use of natural resources. Such present and future energy problems can be solved by the use of renewable energy sources. Among several renewable energy sources is a sustainable means of anaerobic digestion for production of gases. In the past, anaerobic digestion as a source of biogas was used mainly for degradation of waste materials or toxic compounds. However, recently, there has been great interest in producing biogas from energy crops. This paper presents an overview of state-of-the-art and future viewpoints related to the anaerobic digestion process for biogas production.

Keywords: Biogas, Biomass, Anaerobic Digestion, Methane, Renewable Energy

JEL Classifications: Q4, P28

2.1 INTRODUCTION

Due to the fluctuating cost and the environmental effects of conventional sources (especially fossil fuels) of energy, there is an emergent interest in the use of renewable energy. As such, the adoption of renewable energy is gradually becoming significant due to the negative effects of greenhouse gas emissions (GHG) on the environment (Naik et al., 2010, Babatunde et al., 2018, Ighravwe and Babatunde, 2018). Another driver for the use of renewable energy sources is sustainability. It has been said that the conventional sources have a lifespan and will be totally depleted in future (Ighravwe et al., 2018). The common renewable energy sources that have been explored include solar, wind, hydro, geothermal as well as biomass. It is possible to generate biofuels such as hydrogen, methanol, dimethyl ether (DME), ethanol, synthetic natural gas (SNG), etc from biomass. To fully explore the use of biomass in the generation of energy, several government organisations and researchers have instituted programmes and studies to promote the use of biofuels. For instance, the European Union has a target to make biofuel 10% of its energy share in the transport sector by 2020 (Molino et al., 2018). Furthermore, by 2022, the US is expected to produce about 36 billion gallons of biofuels annually (Molino et al., 2018). Presently, industrial plants are embracing the production of biogas for the generation of energy and on biomethane upgrading for grid injection. The production of biogas is noncomplex and centralized technology with a low level of organic conversion into biogas, (nearly 5–10 wt. %), based on the type of feedstock and the operative conditions (Molino et al., 2013b, Molino et al., 2013a).

Nations with enormous area of fertile cultivable land, a favourable climate as well as water resources can invest in the planting of biomass plants for energy generation (Sparks et al., 2014). Such agricultural plants include sugarcane, cassava, corn starch etc. For instance, it is possible to produce several types of sugar, and alcohol as well as generate electricity from sugarcane. The agricultural and industrial processing of these plants yields products such as straws, molasses, filter cake, stalks, pulp etc. which can be further exploited to generate electricity. Conversely, there exist significant logistical challenges related to production of biomass feedstock from food products such as cassava and sugarcane. One of such is the challenge of maintaining a balance between the economic, technical, political, social, and environmental factors involved in the biofuel production processes. Thus, decision makers, researchers and other stakeholders have revolved into the conduct of experimental studies as well as mathematical optimizations techniques that can help in attaining the optimum decision that will make biomass more economically appealing and commercially available. One of the end products of this process that has been of major interest of late is the production of biogas. Biogas (considered to be the low carbon fuel sources) offers the best opportunities to the rural communities especially in African countries to meet their energy demand. The use of biogas offers multiple benefits, such as:

- the enhancement of farming in rural communities, which directly enhances the economy of a community through job creation;
- waste reduction through the use of organic agricultural waste and municipal solid waste (MSW) for energy production;
- the improvement of the environment quality through CO_2 emission reduction (Soccol et al., 2011); and
- the combination of the disposal of organic waste with the formation of valuable energy “methane” by biogas.

The production of biogas is based on a profound technology whose output is principally used for electricity generation and also for the valorization of organic residues (Kougias and Angelidaki, 2018). Biogas is an output of anaerobic digestion, where various microorganisms, breakdown organic matter through different metabolic processes. Tremendous and novel development in biogas production has led to the creation of advanced bioenergy facilities. As such, the biogas facilities are the basis of an economy concept aimed at nutrients recycling, reduction of greenhouse gas emissions and biorefinery purposes. This paper presents an overview of state-of-the-art and future viewpoints related to the anaerobic digestion process for biogas production.

2.2 BIOGAS PRODUCTION

Biogas is a colourless combustible gas that is produced by the biological breakdown of organic matter; occurring in the absence of oxygen (Umeghalu et al., 2012). The biogas comes from “biogenic materials” (Umeghalu et al., 2012), and is generated from anaerobic digestion of biodegradable materials such as biomass, cow dung green waste and agricultural residue such as cassava, sugar cane etc. (Ghosh, 2000). Biogas comprises a mixture of different gases, mainly methane (CH_4), carbon dioxide (CO_2), 1–5% other gases, including hydrogen (H_2), and their typical composition is presented in Table 2-1 (Umeghalu et al., 2012).

The gas is produced by bacteria that occur during the bio-degradation of organic materials under anaerobic conditions (Sutaryo, 2012). Biogas has an elevated methane content (see Table 2-1), which makes it an attractive source of energy and a suitable fuel for heating and cooking purposes globally. Moreover, considering that biogas constitutes mainly methane and carbon dioxide, which are greenhouse gases that are harmful to the environment, it is therefore important that it undergoes a burning process before releasing it to the atmosphere. Biogas generated during an anaerobic digestion process can be converted into electricity and heat using combined heat and power (CHP) engines (Sorathia et al., 2012).

Table 2-1: Biogas composition (Prakash et al., 2005, Schnurer and Jarvis, 2010)

Component	Concentration (%)
Methane (CH_4)	55 – 60
Carbon Dioxide (CO_2)	35 – 40
Hydrogen (H_2)	2 – 7
Hydrogen Sulphide (H_2S)	2
Ammonia (NH_3)	0 - 0.05
Nitrogen (N)	0 – 2

The physical, chemical and biological characteristics of potential biomass materials can influence the biogas composition and yield (Mogami et al., 2006). In general, three key methods are in the thermo-chemical conversion of biomass. The main thermo-chemical conversion processes, the intermediate process and the final energy products resulting from the conversion procedure are given in Figure 2-1.

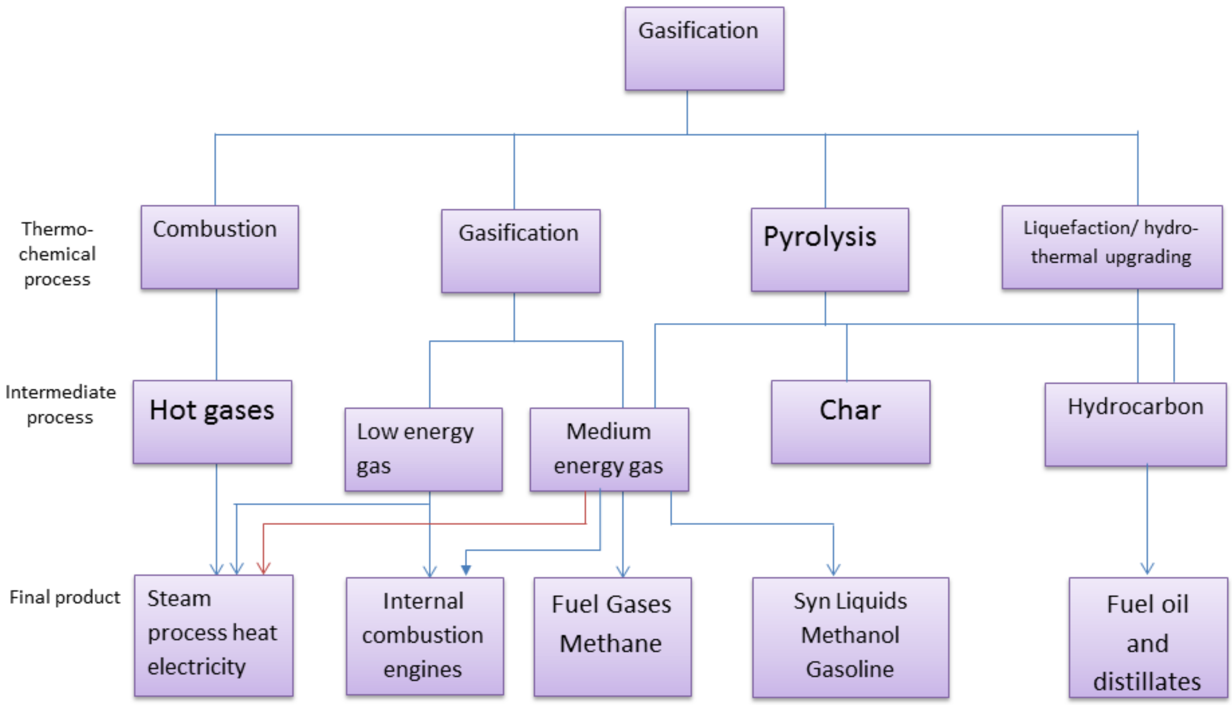


Figure 2-1: The main processes used for the thermo-chemical conversion of biomass (Mckendry, 2002)

2.2.1 Anaerobic digestion

The anaerobic digestion is a microbial degradation of organic waste in the absence of oxygen. Organic matter conversion to CO_2 and CH_4 gases occurs next to a sequence of biochemical reactions during an anaerobic process (Bailey and Ollis, 1986). As a result, a breakdown of organics takes place during the digestion, and this is made possible by anaerobic microorganisms. The anaerobic digestion of organic matter follows stages that are organized by different categories of microorganisms. Most biodegradable organic matter are converted to gases while only a small amount (about 10%) is converted to new cell mass through microbial growth (Speece, 1983). Methane produced by anaerobic digestion can be used to run a treatment plant; giving anaerobic digestion an economic advantage over aerobic digestion. Table 2-2 shows the advantages and disadvantages of an anaerobic digestion taking into consideration costs, start-up time, sludge generation and buffering capacity.

Table 2-2: Advantages and disadvantages of anaerobic digestion process (Seghezzo et al., 1998, Lettinga et al., 1997, Lettinga, 1995)

Advantages of anaerobic digestion process	Disadvantages of anaerobic digestion process
The operating costs for an anaerobic treatment plant are relatively very low compared to an aerobic treatment plant.	Long start-up: the slow growth rate causes as a longer start-up period as compared to aerobic systems.
Low-energy consumption and production of biogas for further applications such as the production of electricity; requiring no external energy for its operation.	High buffer requirements for the pH control: the required pH for anaerobic digestion should be in the range of 6.5 to 8. Also, chemical addition, mostly in industrial wastewater, may be indispensable for the control of pH with inadequate buffering capacity.
The flexibility of an anaerobic system allows the technology to be	High sensitivity of microorganisms: methanogens are sensitive to pH and

Advantages of anaerobic digestion process	Disadvantages of anaerobic digestion process
applied on either a small or a large scale.	temperature, it is assumed that they have less resistance toward toxic compounds.
Low sludge generation compared to aerobic systems due to a lower yield coefficient.	Low pathogen and nutrients removal: effluents generated from anaerobic digestion are characterized by low removal of pathogens and nutrients. A post-treatment process such as membrane filtration is required to meet the discharge guidelines aiming to protect the environment.
The excess sludge is well stabilized thereby resulting to limited environmental impact.	The process is more sensitive to the presence of toxic compounds and changes in temperature than aerobic systems.
Low nutrient and chemical requirement: this is due to the small biomass production during an anaerobic process; consequently, the nutrients requirement is proportionally less.	
Allows for efficient resource recovery, and conservation of non-renewable energy sources.	

2.2.2 Stages of biogas production using anaerobic digestion

There are four basic stages involved in anaerobic digestion (AD). These four basic stages make up the process of biogas production from various organic materials as it occurs in an anaerobic digester. These four stages are the hydrolysis, acidogenesis, acetogenesis, and methanogenesis as outlined in Figure 2-2 (Tutuk, 2011). The AD process is characterized by the decomposition of organic matter into methane, carbon dioxide, inorganic nutrients and compost in an anaerobic environment (Arsova, 2011, Ayu and Dyan Aryati, 2010).

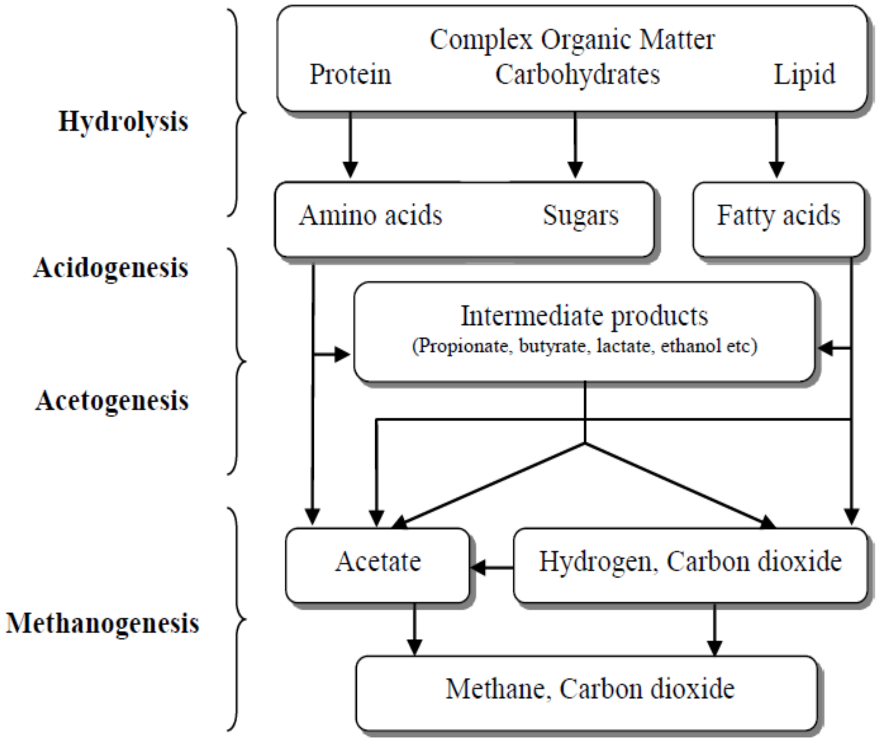


Figure 2-2: Biochemical stages of anaerobic digestion/biogas product (Jewitt et al., 2009)

Hydrolysis

Hydrolysis is the first step in an AD process. It is achieved through the solubilization and degradation of biopolymer particulate organic compounds and colloidal wastes into soluble monomeric or oligomeric organic compounds (Gerardi, 2003). This process involves the decomposition of complex organic polymeric materials such as carbohydrates, proteins and lipids. These complex organic compounds are hydrolyzed into smaller, water-soluble compounds such as sugars, amino acids, and long chain fatty acids by enzymes produced by the fermentative bacteria (microorganisms) (Eastman and Ferguson, 1981). At the end of the hydrolysis stage, a simple organic compound is produced. These products thereafter undergo absorption and degradation by different facultative and obligate anaerobic bacteria in the acidogenic step, producing short-chain volatile fatty acids (VFA). These combine with alcohols and are converted to acetate, hydrogen and carbon dioxide (Chandra et al., 2012). This phase involves hydrolyzing polysaccharides into monosaccharides, fats into glycerine and fatty acids and proteins into amino acids (Parawira et al., 2004, Lyilade, 2009). The enzymatic catalysis accelerate the hydrolysis process through oxidation of the organic matter via a process called aerobic biological processes (Pisano, 2007). The hydrolysis and aerobic degradation process is a rapid process and the biogas produced is transformed into carbon dioxide (CO_2) from oxygen (Pisano, 2007). When the substrate has been hydrolyzed, it becomes available for cell transportation and the fermentative bacteria can then degrade these substrates during the acidogenesis stage. Optimization of the hydrolysis process is, however, important to prevent inefficient degradation of the macromolecules, which could impact negatively on the rate of digestion or other biological activities, and consequently the biogas yield. It is therefore important to make sure that the culture of microorganisms is actively operational to allow the second process (acidogenesis) to take place. Physicochemical treatments can also be used to promote solubilization of organic matter. However, there should not be air intake in the system, as the presence of air in the biomass prevents the biomass from performing their duties as anaerobic units.

Acidogenesis

The process of acidogenesis transforms the organic acid that is produced during the second stage into acetic acid, acid derivatives, carbon dioxide, and hydrogen. According to (Fang et al., 2010), it is essential that the level of H_2 is low for acidogenic reactions to be favourable thermodynamically. In this stage of the AD process, the products of the hydrolysis stage are further broken down by a variety of obligate and facultative fermentative microorganisms to produce weak acids (mostly organic acids) such as acetic acid, propionic acid, butyric acid (VFAs), lactic acid, alcohols, hydrogen and carbon dioxide (CO_2) (Kalyuzhnyi et al., 2000). The acidogenesis stage involves the production of high concentration of hydrogen by acid-producing bacteria called acidogenic microorganisms and is usually the fastest step in a balanced anaerobic process. Acidogenesis is mainly described by the accumulation of lactate, ethanol, propionate, butyrate, and higher VFAs called electron sink or intermediate products. Acidogenesis is the bacterial response to increased hydrogen concentration in the system to produce acetate by acetogenic microorganisms (Schink, 1997). The degradation of organic matter to generate biogas also depends on the complex interaction of various groups of bacteria, with the two main groups being the acid-producing bacterial (acidogens) and the methane-producing bacteria (methanogens). Therefore, maintaining a symbiotic relationship between the acidogenic and methanogenic bacteria is critical in sustaining the successful operation of any anaerobic digester (White, 2011). This step is critical because it links the fermentation phase with the methane production phase. Thus, more acid is produced to give birth to methanogens elements, which produce methane gas.

Acetogenesis

During the acetogenesis stage, alcohols (ethanol), VFAs with more than two carbon atoms, are converted by acetate-forming bacteria into acetate, with hydrogen and carbon dioxide being the main products (Parawira et al., 2004, Gerardi, 2003). This conversion is a vital process because hydrogen and carbon dioxide are constantly reduced to acetate by homoacetogenic microorganisms (Chandra et al., 2012), thereby reducing the hydrogen accumulation that may affect the functioning of acetogenic bacteria (Weiland, 2010). Low hydrogen partial pressure (10.4 and 10.6 atm) is required for the acetogenic reaction to proceed (Mccarty and Smith, 1986). This is because acetogenic bacteria can survive in a very low hydrogen concentration environment. However, further increase in the concentration of hydrogen partial pressure may result in acetogens losing their ability to produce acetate. In order to ensure that low pressure is maintained all through the acetogenesis stage of the AD process, a mutually symbiotic relationship between the acetogens and the hydrogenotrophic methanogens must occur, so that acetogens produce acetate that can be used as substrate by methanogens (Nges et al., 2012). This step constitutes the final phase for fermentation prior to methanogenesis.

Methanogenesis

Methanogenesis is a critical step in AD. It has a large impact on the AD process (De Vrieze et al., 2012) because approximately 70% of methane used in AD is generated from this stage (Sutaryo, 2012). During this stage, carbon dioxide-reducing and hydrogen-oxidizing methanogens convert hydrogen and carbon dioxide to obtain methane, while acetoclastic methanogens utilize acetate to produce methane (Parawira et al., 2004). Methanogens (Archaea) utilize acetate, hydrogen and CO_2, and to a lesser extent methanol, methylamines and formate, to form methane and CO_2. These end products are the primary substrates for the methanogenic bacteria to produce biogas, which generally consists of 50–75% methane (CH_4), 50–25% CO_2 and trace amounts of nitrogen, hydrogen and hydrogen sulphide. Methanogenesis indicates the extent of biological activities in an anaerobic system and the state of the digestion. The more methane is produced, the more the system is stable and well performing.

2.3 MAIN FACTORS AFFECTING THE BIOGAS PRODUCTION

The production of biogas is influenced by many factors such as nutrients, pH of feedstock, temperature, flow rate of feed (loading rate) and retention time. These factors may slow or stall the process of biogas production if the values of the factors are not within a certain range (Angelidaki et al., 2009). Some of the factors are presented in this section.

2.3.1 Hydraulic retention time

Hydraulic retention time (HRT) indicates the mean residence time for solids and liquids wastes remaining in a digester (reactor) to contact with the microbial biomass (Khanal, 2008). In flow-through systems without recycle, such as the CSTRs adopted in Phase II, the HRT and retention time of the microbial biomass or sludge (SRT) are the same. In situations where the influent streams contain high solids concentrations, longer retention times are required to maximize bioenergy production (Khanal, 2008). The HRT can be understood as the treatment time for a waste that undergoes anaerobic digestion, the higher the HRT, the higher the removal efficiency because the biomass has enough time to be in close contact with the waste. Therefore, removing high amounts of contaminants from the waste being treated.

2.3.2 Nutrients

The inadequate availability of nutrient concentration in energy crops have resulted in problems such as low methane yields, acidification and process instability in crop mono-digestion, leading to application of low organic loading rates (OLRs) and long HRTs (Lebuhn et al., 2008, Weiland, 2010). They influence the performance and stability of the AD process (Hinken et al., 2008, Lebuhn et al., 2008, Scherer et al., 2009). The above mentioned setbacks indicate that adequate amounts of both macro- and micronutrients (Bruni et al., 2010) are crucial for continuous performance of the biogas process.

2.3.3 pH of feed stock

The pH value of the material is one of the essential factors. Methanogenic bacteria are sensitive to an acidic condition. This acidic condition could adversely affect the growth of bacteria and the production of methane (Arsova, 2011). Different optimal pH values are reached at different stages of the AD process. These changes occur during biological transformation, which takes place during the different stages of the AD process. The pH level can be below 5 during the production of organic acids, which occurs during the acetogenesis stage (Arsova, 2011). According to Liu et al. (2008), the optimal range of pH for obtaining utmost biogas yield in anaerobic digestion is 6.5–7.5, and this range of pH is relatively wide in plants. Several factors such as the substrate used and the digestion technique could vary the optimal value of the pH. For this reason, constant pH level is of great importance, and to maintain a constant pH level, equilibrium buffers such as calcium carbonate or lime must be added into the system. Briefly, pH is a critical indicator in anaerobic process. It provides a clear indication of the performance of the system, including the stability of the digestion. A lower pH is an indication of system failure or low buffering capacity and can inhibit the digestion. High pH can also limit the methanogenesis process. The pH value is dependent on the following factors: volatile fatty acid (VFA) concentration, bicarbonate concentration, the alkalinity of the system and the fraction of CO_2 in digester gas. According to Liu et al. (2008), the relationship between the VFA and bicarbonate concentration is crucial to maintain a constant pH value within the system.

2.3.4 Temperature

As reported in Davidsson et al. (2008), AD is usually operated within two distinct temperature ranges, with one optimum at 35 °C (mesophilic) and the other at 55 °C (thermophilic). Though thermophilic digestion may provide some advantages over mesophilic digestion, such as improved reaction rate and pathogen reduction, microorganisms in mesophilic digestion have less demand on nutrients (Takashima et al., 2011), making mesophilic digestion function like thermophilic digestion (Nges et al., 2012). Temperature indicates the rate of biological reactions. It is a sensitive parameter that must be monitored regularly, especially when there is a change in weather. The choice of temperature (mesophilic or thermophilic) will depend on the type of expected outcome. However, temperature should be suitable to the type of microorganisms used for waste treatment.

2.3.5 Organic loading rate

The amount of substrate (biomass) fed into the unit reactor system is called the OLR and is commonly expressed in terms of chemical oxygen demand kg / m^3day, volatile solids (VS) of total solids (TS)/ L day or VS / m^3 day. It has been reported that the AD of solid wastes in a single stage may encounter problems if the OLR is increased above the system capabilities and if the hydrogen and the VFAs formed by the acidogenic bacteria are not consumed at the same rate by the methanogens. This is because acidogenic activity and the VFA intermediates produced in the acid forming stages triggers an increase in the acidogenic bacteria at higher OLRs, thereby reducing the growth of the methanogenic population. The increase in OLR and acidogenic activity (production of VFA, CO_2 and H_2) can result in an accumulation of organic acids and a decrease in pH and gas production. This in turn affects the biological activity of methane-producing methanogens as their growth is inhibited below a pH of 6.6, therefore reducing the production of methane, which is the main product of biogas. Therefore, determining the correct OLR for a particular substrate is critical for the optimization of reactor performance and maximizing methane production. The methane yield is generally measured by the amount of gas that can be produced per unit volume of VS contained in the feedstock after exposing it to anaerobic digestion for a sufficient amount of time under a given temperature and specific conditions (Zhang, 2012). The methane yield is also an indication of the biodegradability of the substrate, as feedstock with low VS to total solids ratios (VS/TS), such as lignin, are not easily degraded using anaerobic processes. Therefore, the amount of gas produced is also very much substrate dependent.

2.3.6 Retention time

A longer retention time will provide a greater degree of sludge stabilization and allow intimate contact between the biomass and the liquid flow during the treatment process (Keay).

2.3.7 Mixing

In a conventional anaerobic digester, mixing has been observed to generally increase CH_4 yields and to render the digester more stable (Forday and Greenfield, 1983). Mixing has the effect of bringing a homogeneous environment and an effective use of the entire digester volume. This is achieved by minimizing hydraulic dead zones in the digester and preventing build-up of large pockets of unfavourable environmental conditions (low pH and high VFA). Consequently, the concentration of toxic agents throughout the reactor is diluted. Mixing also assists in the removal of excess CO_2 which has inhibitory effects at partial pressures larger than 0.2 atmospheres (Pulles et al., 2001).

2.3.8 Oxygen

Oxygen is toxic to most anaerobic microorganisms. Its presence in an anaerobic reactor will result in a significant decrease in the digestion rate. However, it is possible that facultative anaerobes metabolize the dissolved oxygen before toxic effects are noticeable (Zinder and Koch, 1984).

2.3.9 Volatile fatty acids (VFA)

During start-up or when there is organic overloading of the digester, high concentrations of VFA are generally observed. They are usually associated with toxicity and inhibitory effects. Although it is generally understood that VFA inhibition is due to their accumulation and subsequent pH reduction, some VFA are themselves toxic to anaerobic microbes (Mara and Horan, 2003).

2.3.10 Free ammonia

Free ammonia concentrations above 100 mg/l can cause inhibition, although the ionic form, NH^{+}_{4}, will only cause inhibition at much higher concentrations (above 3000 mg/l) (Rittmann and Mccarty, 2012).

2.4 METHODS OF BIOGAS PRODUCTION THROUGH ANAEROBIC DIGESTION

Anaerobic digestion turns organic waste into useful biogas and fertilizer in an anaerobic environment (De Meester et al., 2012). There are two main methods to produce biogas from anaerobic digestion namely, wet anaerobic digestion (Wet AD) and dry anaerobic digestion (Dry AD). The main difference between these two methods relates to the form of the solid waste. Dry AD handles organic waste as it is by means of simple mechanical sorting and with digestion taking place from waste in its solid form. Wet AD requires that the waste be converted into a homogenous pulp that can be pumped while being processed. Biogas produced during anaerobic digestion is mainly composed of methane and carbon dioxide and is considered as an alternative to traditional energy (Khanal, 2008). Typically, it contains 60–65% methane, which is flammable. With the technology of biogas utilization improving, it becomes one of the most widely used waste/residues-to-energy technologies (Khanal, 2008). Traditionally, biogas has been used as fuel to support the process temperatures in anaerobic digesters. Another alternative use is that the gas is burned in an engine generator of combustion to produce electricity in biogas plants. Biogas has also been used as fuel for cooking, lightning and vehicles (Khanal, 2008).

Biogas production, except for its use as a renewable energy source, has many other benefits. In many countries, farmers must give up their occupations because their land no longer produces enough yield from conventional agricultural production. Biogas production is subsidized in many countries to give an additional income to the farmers. There is an increase in wider unused agricultural areas and farms becoming large-scale industries, which will change the landscape (Branche, 2017). Biogas production with small-scale farm production could maintain the structure of the landscape. Energy can be generated from the unneeded biomasses, which can save the natural resources. Comparing anaerobic degradation metabolism products to aerobic ones, organic acid and methane contain higher energy than low-energy compounds like CO_2

and H_2O, which serve other organisms as nutrients or energy as 20 times as much as the energy lost to air. Biogas plant can also reduce landfill area and protect groundwater quality (Paolini et al., 2018).

Due to anaerobic processes, organic matters can be reduced to 4%, which reduces landfill area and protects the groundwater (Mahar et al., 2007). Furthermore, because the reduction of biomass is significant, the reuse of the residue from biogas processes, such as fertilizers, can cut down the expenditure of organic wastes. If co-substrates are used in biogas plants, mineral fertilizers can be replaced by residue. The advantages include cutting down expenditure. Co-substrates can reach the cycle of nutrients and reduce nitrate leaching. Methane and nitrous oxide emissions are reduced when residue and manure are digested instead of being spread on the field or stored. The digested residue produced is less odorous (Linville et al., 2015). This process also supports the Kyoto agreement of climatic protection by achieving CO_2-neutral production of energy. It can reduce the fees for the management of wastewater and avoid the connection of sewers, especially in rural areas. Furthermore, a significant reduction in pathogenic germs could be derived from the digested residue after an anaerobic process.

2.5 TYPES OF BIOMASS AND THEIR POTENTIAL

Biomass is defined as a living organic matter (Fry, 1988). Biomass can be any type of organic matter and it is a source/feedstock. The fuel form obtained after the processing or preparation of this biomass is called biofuel, biogas or bio-solid and the energy output is called bioenergy, which is a measure of the energy capability of the biomass used. An extensive range of biomass is available for the potential sources for CH_4 production as shown in Figure 2-3.

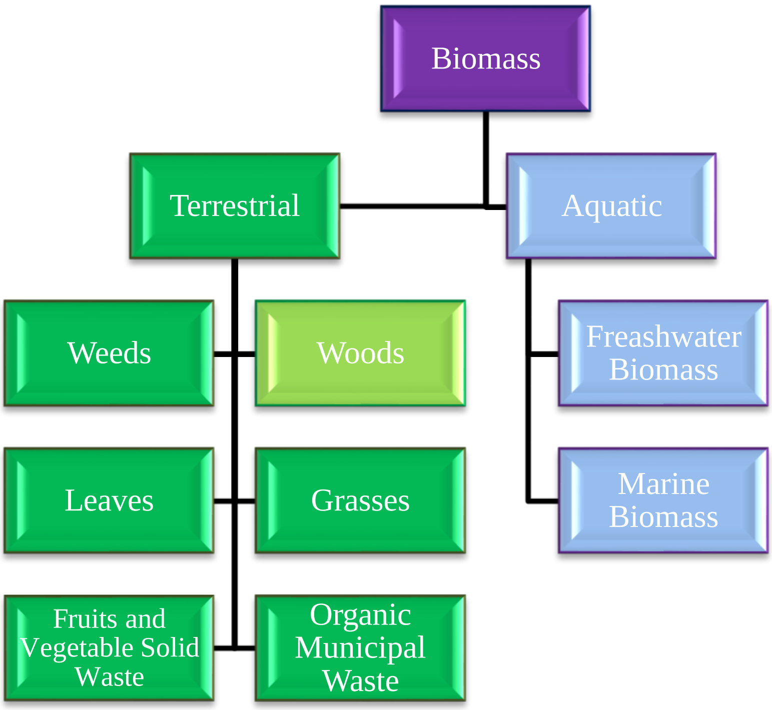


Figure 2-3: Methane yield from different biomasses (Luna-Delrisco et al., 2011)

2.5.1 Terrestrial biomass

Biogas from woods and weeds

Anaerobic digestion of woody biomass for biogas production has been considered unfeasible without pre-treatment (Gunaseelan, 1997) due to its anaerobic biodegradability, which depends on the following factors: low moisture content; relative lignin; cellulose and hemicellulose content; proportion of structural and non-structural carbohydrates; cellulose crystallinity; degree of association between lignin and carbohydrates; particle size; wood-to-bark ratio; and toxic components (Turick et al., 1991). Table 2-3 shows that hybrid poplar and sycamore with high degradability produced the highest CH_4 yield of 0.32 m^3/kg VS using the BMP assay test, while according to (Tong et al., 1990) eucalyptus, loblolly pine and white fir on poor degradability yielded 0.014, 0.063 and 0.042 m^3/kg VS of CH_4 respectively at mesophilic temperature.

The use of weedy plants as a potential feedstock for biogas production is a recent concept. It is considered a potential biomass for the following reasons (Nallathambi Gunaseelan, 1997):

- Ability to trap a significant amount of solar energy.
- Weeds can grow on soils unsuitable for conventional crop production under a wide range of climatic conditions.
- Weeds are not easily affected by pests.
- Weeds grow without inputs and irrigation.
- The use of weeds for biogas production is considered the best strategy of weed management and control.

Table 2-3 shows some of the weeds studied as a source of CH_4, these weeds include Parthenium hysterophorus, Lantana camara, and Ageratum. According to Gunaseelan (1994), the batch co-digestion of cow manure (Bozkurt et al., 2016) and Parthenium has shown to increase the production of biogas using Parthenium. Anaerobic digestion of Parthenium in CSTR at a temperature of 30°C with a 10-day HRT yielded CH_4 of 0.11 m^3/kg VS while pre-treated Parthenium increased the CH_4 yield by 95% (Table 2-4). Lantana camara, a weed that grows abundantly on the Himalayan slope, India, treated with NaOH and mixed with CM to feed batch digesters for 37 days at a temperature range of 28–31 °C produced 62% higher CH_4 yield compared to CM alone (Dar and Tandon, 1987, Gunaseelan, 1994). Table 2-4 shows that Ageratum alone (mono digestion) yielded 0.24 m^3/kg VS added of CH_4 yield in batch digesters at a temperature of 30 °C (Kalia and Kanwar, 1990).

Table 2-3: Methane yield of woody biomass

Feed stock	Fermenter	Temperature (°C)	Methane yield (m^3/kg VS)	VSr (%)	Reference
Cotton wood	BMP	35	0.220	32.3	(Gunaseelan, 1997)
Hybrid poplar	BMP	35	0.320	53.8	
Sycamore	BMP	35	0.320	56.7	
Loblolly pine	BMP	35	0.063	3.6	
Eucalyptus sp	BMP	35	0.014	1.0	
Black alder	BMP	35	0.240	32.5	
Red alder	BMP	35	0.280	48.4	
White fir	BMP	35	0.042 ± 0.003	NR	(Tong et al., 1990)
Willow	BMP	35	0.140 ± 0.01	NR	(Turick et al., 1991, Chynoweth et al., 1993)
Stem and bark 0.8 mm particle size	BMP	35	0.310 ± 0.01	NR	
Poplar stem and bark	BMP	35	0.290 ± 0.010	NR	
Sweet gum	BMP	35	0.210 ± 0.010	NR	
Poplar wood - 0.003 mm size	BMP	35	0.330	NR	(Chynoweth et al., 1993)

BMP = Biochemical methane potential; VSr = Volatile solid reduction; NR = Not recorded

Table 2-4: Methane yield from weed biomass

Feed stock	Fermenter	Temperature (°C)	HRT (days)	OLR (kg VS m3/day)	Methane yield (m3/kg VS)	VSr (%)	Reference
Parthenium Hysterophorus (PH)	Semi-continuous	28 – 32	5	4.95	0.034 ± 0.002	25.9	(Gunaseelan, 1994)
PH, untreated, daily Feed			10	2.48	0.117 ± 0.005	42.9	
			20	1.24	0.115 ± 0.001	42.1	
Lantana camera, NaOH Treated + CM (50:50 w/w)	Batch 3l	28-31	NA	NA	0.236	NR	(Dar and Tandon, 1987)
Ageratum, partially decomposed	Batch 3l	29-31	NA	NA	0.241	NR	(Kalia and Kanwar, 1990)

NA = Not available; NR = Not recorded; HRT = Hydraulic retention time; OLR = Organic loading rate
VSr = VS reduction

Biogas from leaves and grass

According to Chynoweth et al. (1993), methane produced from leafy biomass are generally higher compared to that produced from the stems (Table 2-5). Sharma et al. (1988) reported higher CH_4 yield in Ipomoea jistulosa leaves than in its stem. According to Gunaseelan (1988), Gliricidia leaves green-leaf manuring found in India when it undergoes anaerobic digestion yielded a CH_4 of 0.18 $m^3/kg\ VS_{added}$ when co-digested with residue of high manorial value. However, some leaves with the presence of some toxic compound produced low CH_4 due to partial inhibition of the digestion process. One such leaf is Calotropis (Mahamat et al., 1989). Research conducted by Shyam and Sharma (1994) showed that the batch digestion of high solids with mango leaves and cow manure (Bozkurt et al., 2016) produced higher biogas yield compared to digestion of CM alone.

Research has shown that grasses such as Napier grass, energy cane (ball milled), Alemangrass-6A, turf grass, wheat straw, paddy straw, millet straw, oats crop, maize crop, corn stover and sorghum have exhibited CH_4 yields as high as 0.3 m^3/kg VS added without pre-treatment (Chynoweth et al., 1993). As reported by (Turick et al., 1991), the grass with the highest yield of CH_4 is sweet sorghum. The age of the grass has also been found to play an important role in CH_4 production. Younger grasses often produce more methane than the older ones, probably because younger tissues are less lignified (Shiralipour and Smith, 1984).

Table 2-5: Methane yield from grassy biomass (Gunaseelan and Lakshmanaperumalsamy, 1990, Gunaseelan, 1995, Yang and Li, 2014)

Feedstock	Fermenter	Temperature (°C)	Hydraulic retention time (days)	Organic Loading Rate (kg VS m^3/day)	Methane yield (m^3/kg VS)	VSr (%)	Reference
Penniselum Purpureum (Napier Grass)							
Age: 120 days	BMP	35	NA	NA	0.310	NR	(Gunaseelan, 2007)]
180 days					0.260		
Energy cane							
Ball milled	BMP	35	NA	NA	0.320	NR	
Particle size 0.8mm					0.240		
Particle size 8.0mm					0.290		
Grass mixture							
Wheat straw							
20 mm size	Batch l litre	35-39	NA	NA	0.255	79	(Ge et al., 2014)
0.5 mm size				0.327		91	
Sugarcane hybrids							
US 72-1288	BMP	35			0.277 ± 0.028	NR	

Biogas from fruit and vegetable solid waste (FVSW) and organic municipal solid waste (OMSW)

The organic fraction of MSW has been identified as a diverse material of which the composition differs greatly. Many factors affect the composition of MSW, including regional differences, climate differences, the extent to which recycling is done, the frequency of collection, seasonal change, and cultural practices (Tchobanoglous et al., 1977). The sorting system of MSW is not the only factor that influences the quality, they are also influenced by various methods used for quantifying the OMSW. According to Mata-Alvarez et al. (1990), mechanical sorting of MSW is present in large amounts of suspended, non-biodegradable solids and small pieces of plastic, wood and paper. OMSW digestion at a mesophilic temperature (35°C) yields a maximum CH_4 ranging from 0.39 to 0.43 m^3/kg VS MSW without paper and wood (Mata-Alvarez et al., 1990) and VS reduction (VSr) ranging from 63 to 69% (Table 2-6). The methane yield of OMSW ranged from 0.11 to 0.16 m^3 kg- VS and VSr was around 30% due to its high ash value (Mata-Alvarez et al., 1990).

The FVSW wastes are characterized by high percentages of moisture (> 80%) and VS (> 95%) and have a very high biodegradability percentage. Table 2-6 shows that the CH_4 yield of FVSW is very high. However, these results are mostly based on laboratory trials. According to Knol et al. (1978), the maximum OLR to obtain a stable digestion of a variety of FVSW ranges from 0.8 to 1.6 kg VS mm^3/d having an HRT of 32 days. According to Hills and Roberts (1982), the failure of the digestion of peach waste is due to inadequate alkalinity levels at 3 kg/m^3/d with a 20 days HRT.

Research conducted by Radhika et al. (1983) show that coconut pith (Snyman and Botha) co-digested with cow manure (Bozkurt et al.) performed better with a mixture ratio of 3:2 dry weight basis that also showed enhanced biogas production with 80–85% CH_4. According to a study conducted by Stewart et al. (1984) where the biogas yield from the AD of banana, i.e. damaged fruit and stem, and potato waste was measured (peelings and rejects). The digestion was done in a 20 *litres* continuous digester at a temperature of 35 °C. The greatest CH_4 yields were obtained from the complete digestion of the banana waste, which is almost a complete destruction of the VS. For a HRT of 20 days with OLR 2.5 kg TS/m^3/d, the CH_4 yield for banana waste was 0.53 m^3/kg VS at 100% VS conversion.

Table 2-6: Performance of municipal solid waste at mesophilic temperatures

Substrate	Fermenter	Temperature (°C)	Hydraulic retention time (days)	Organic loading rate (kg VS m3/day)	Methane yield (m3/kg VS)	VSr (%)	Reference
MS-OMSW	Laboratory plant	35-40	16 - 21	10	0.260	NR	
Conc = 30-35% TS	0.035 m^3			12.1	0.264		(Lemmer and Oechsner, 2002)
	Dranco process				0.260		
Conc = 25-35% TS	60 m^3	35 - 40	14 - 21	15	0.187	NR	
Yard waste	BMP	35	NA	NA	0.209	NR	(Owens and Chynoweth, 1993)
Grass, VS = 88.1%TS					0.123		
Leaves, VS = 95% TS					0.134		
Branches, VS = 93.9%TS					0.140		
Blend, VS = 92% TS				NA	0.255		
Paper Waste							
Office, VS = 92.7%TS	BMP	35	NA	NA	0.369	NR	(Owens and Chynoweth, 1993)
Printed newspaper VS = 97.6% TS					0.100		
Unprinted newspaper, VS = 97.9%TS					0.084		
Magazine, VS = 78.1%TS					0.203		

2.5.2 Aquatic biomass

Biogas production from aquatic biomass may be greater when compared to those obtained from land considering the availability of large areas for growth. Terrestrial biomass production is two-dimensional, while aquatic biomass production is three-dimensional where the “height” is added.

Biogas from marine biomass and fresh water biomass

Recent studies on marine biomass involve the bioconversion of marine macroalgae to a potential source for CH_4. This includes the brown algae *Macrocystis pyrifera*, *Sargassum*, *Laminaria* etc. Table 2-7.

Table 2-7: Summary of biomass with high methane yield

Biomass	Methane yield (m^3/kg VS)	Reference
<u>Organic municipal solid waste</u>		
HS-OMSW	0.390	(Cecchi et al., 1986)
SC-OMSW	0.403	(Mata-Alvarez et al., 1990)
SS-OMSW	0.399	
<u>Fruit and vegetable solid waste and leaf</u>		
Potato waste	0.426	(Stewart et al., 1984)
Carrot waste	0.417	(Shen et al., 2013)
Banana fruit and stem	0.529	(Murphy et al., 2011)
Tomato processing waste	0.420	(Sarada and Joseph, 1994)
Banana peeling	0.409 ± 0.002	(Izumi et al., 2010)
<u>Grassy biomass</u>		
Sorghum	0.420	(Gunaseelan, 2004)
Corn stover	0.360	(Gunaseelan, 2007)
Paddy straw	0.367	(Mshandete et al., 2006)
Milet straw	0.390	(Mahamat et al., 1989)
Wheat straw	0.383	(Hashimoto, 1986)

Biomass	Methane yield (m^3/kg VS)	Reference
Woody biomass		
Iponnoea stem	0.426	(Seppälä et al., 2007)
Poplar wood	0.330	(Gunaseelan, 2004)
Pre-treated vine shoot	0.315	(Odlare)
Weed Biomass		
Lantana treated with NaOH + cow manure	0.236	(Dar and Tandon, 1987)
Partially decomposed *Ageratum*	0.241	(Kanwar and Guleri)
Parthenium treated with NaOH	0.236	
Marine biomass		
Ulea and *Chaetomarpha*	0.480	(Hansson, 1981)
Ulea	0.330	(Bohutskyi and Bouwer, 2013)
Maerocystis Pyrifera	0.310	(Ogut et al., 2013)
Freshwater biomass		
Pisitia	0.410	(Nipaney and Panholzer, 1987)
Water hyacinth treated with NaOH	0.362	(Chynoweth et al., 1982)

2.6 FUTURE STUDIES

The global demand for energy is increasing with the steady growth of the world population, economic growth and increased energy usage. Reliance on fossil fuels has also increased over the years and will soon result in the depletion of fossil fuel resource. It is therefore crucial that current research studies explore alternative energy sources that are sustainable and renewable for future generations. The renewable energy generation during anaerobic digestion of biomass has mainly been used for the degradation of biomass or any waste materials or toxic compounds. However, recently there has been increased interest in the production of biogas from carbohydrate rich energy crops by means of anaerobic digestion. Since cassava is enormously grown in Africa, extensive experimental studies into different nomenclature that can give high yield of biogas from cassava can be performed. Some of the research questions may include:

- Can cassava single and co-digested with vegetable and fruit waste be a successful and suitable anaerobic digestion feedstock for biomass renewable energy in Africa?
- Can the link between peeled and unpeeled cassava tubers be exploited to evaluate biogas yield from cassava and the effect of the cassava peels on the yield?
- How can cassava as an energy crop be used as a landfill cap in decommissioned landfills in Africa for purpose of biogas energy generation?

Future studies should also focus on (i) technology selection via conducting small scale biogas projects; (Lehtomaki, 2006) scheduling under uncertainty of feedstock supply; (iii) farmers perceptions on biomass crops; and (iv) the impact of biomass plant production on host communities. Furthermore, assessment of small-scale biogas production subsidies in rural communities and employment issues can also be investigated. Investigations into these research gaps will strengthen biogas production management and sustainability in rural communities.

2.7 CONCLUSION

A review of the anaerobic digestion process and biogas production has been presented in this study. Technologies and processes involved in the production of biogas from AD have proven to be a valuable means for alternative renewable energy generation. Within the anaerobic domain, several important factors (pH, temperature, retention times, and availability of nutrient and organic loading rates) were identified to exert a high degree of influence on the different steps of the digestion process. In addition, depending on the source of the waste stream, several toxic or inhibitory compounds could be harmful to anaerobic digestion, thereby affecting biogas production and/or methane gas concentration. The evaluation and optimization of the anaerobic process should therefore be considered as an important step towards the realization of optimal biogas production from the AD process. It would help in obtaining the necessary information on waste components crucial for successful application of anaerobic digestion. Furthermore, continued research on AD is suggested, especially in aspects relating to (i) evaluation of different types of waste streams and biomass feedstocks as substrates for different digester configurations; and development of processes that would increase the kinetics reaction, to increase the CH_4 yield.

CHAPTER 3:

IDENTIFICATION AND CHARACTERIZATION OF POTENTIAL FEEDSTOCK FOR BIOGAS PRODUCTION IN SOUTH AFRICA

Nathaniel Sawyerr[1*], Cristina Trois[2], Tilahun Workneh[3]

[1,2]Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

*e-mail: sawyerrnathaniel@gmail.com

e-mail: trois@ukzn.ac.za

[3]Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

e-mail: seyoum@ukzn.ac.za

PREAMBLE

Given that the sustainability of the anaerobic process depends on the availability and properties of the selected feedstock, it was important to conduct an analysis of the feedstock to create a baseline of the study. This chapter presents the identification and quantification of potential feedstock material for biogas production. It also highlights the different feedstock selected for this research. A comprehensive method of sampling and analysis in terms of characterization is presented in this chapter. The physiochemical results of the selected feedstock are presented in this chapter.

This chapter is written in the form of a journal article, as published in *Journal of Ecological Engineering JEENG-01016-2019-01.* The copy of the original article under review is in Appendix P2 as indicated in the declaration section.

https://doi.org/10.12911/22998993/108652

Received 16 March 2019; Revised 19 April 2019; Accepted 06 May 2019; View online at Journal of Ecological Engineering (www.jeeng.net)

ABSTRACT

Biogas is produced during anaerobic digestion (AD) of biodegradable organic materials and is considered a promising renewable energy resource. Feedstocks are essential to ensure successful anaerobic digestion in biogas digesters. Therefore, the search of appropriate substrates has come into focus. In this study, we examined the potential substrates that could be used as feedstock for successful operation of an anaerobic digester. The approach used in this study was to identify the potential feedstocks that can be converted into value-added products. The identification of the feedstocks was done based on classification and by evaluating the theoretical biogas and methane production during the digestion process. Results show that all the substrates considered exhibited biogas theoretical yield, with cattle manure producing the highest yield (0.999 m^3/kg VS), whereas the lowest biogas yield (0.949 m^3/kg VS) was obtained from cassava peels. It was concluded that the use of cassava co-digested with fruit and vegetable waste as an alternative feedstock offer greater potential in terms of biogas production and could thus be implemented in biogas projects running with cow dungs inside South Africa, especially in rural communities.

Keywords: Cassava; fruit and vegetable; Anaerobic co-digestion; Biogas; Methane theoretical production

3.1 INTRODUCTION

The clamour for the reduction of GHGs and the need for sustainable energy and environment has increased research efforts into alternative fuels from renewable energy sources including bio-resources (Achinas et al., 2017). Studies have suggested that, in order to ensure the sustainability of future energy needs, more research efforts should concentrate on renewable energy. Furthermore, the demand for energy is rapidly on the increase with approximately 88% of the world energy based on fossil fuels (Heubaum and Biermann, 2015). Conventional fuel sources such as coal, crude oil and natural gas are not present in commercial quantity throughout the world. This has left many countries to be energy-dependent on countries with abundant quantities. Political instability of the regions with commercially abundant oil and gas may translate to insecurity of energy supply in many countries that import these products. Since human and animal wastes are available in every part of the world, biogas (extracted from biomass) will play a critical role for the future in energy (Achinas et al., 2017). Biogas, which is produced through anaerobic digestion (AD), has proven to offer a major advantage of being environmentally friendly and energy efficient when compared to other forms of energy based on AD technology (Van Foreest, 2012, Achinas et al., 2017).

The sustainability of AD processes depends on the availability and supply of substrates. Therefore, the identification and quantification of potential feedstock material input is of great importance (Gogela et al., 2017). Without enough suitable material as feedstock, the process of anaerobic digestion will be impractical. Selecting a suitable potential material is the starting point in the process design. Additionally, accurate preparation and use of the feedstock is vital for the biogas digester to run effectively and to its maximum potential (Goemans, 2017). Generally, all kind of biomass can be used as substrates for biogas production as long as it has proteins, cellulose, carbohydrates, fats and hemicellulose (Bond and Templeton, 2011). However, depending on the organic content, the amount and quality of methane produced differ from one feedstock to the other (Hagos et al., 2017). The methane content in the biogas indicates the energy value of the biogas, therefore the quality of a selected feedstock plays an important role in terms of the biogas produced. Low biogas production may indicate low methane content which signify low energy value (Nnfcc, 2016). For example, according to Dussadee et al. (2016), maize produces more methane in biogas per m^3 than livestock manure, while livestock manure produces greater methane content as compared to human sewage.

The classification and selection of biomass can help in the construction of a database to determine the biogas yield and the rate at which the biogas is produced. Certain factors should be considered to select a viable feedstock. These include:

1. The feedstock should be available in sufficient quantities for the biogas plant to be feasible for a 10 to 20 year lifespan (Nnfcc, 2016)

2. The feedstock should have sufficient potential to add value (Jordaan, 2018).

3. Fresh and suitable moisture content. Feedstock left in the sun for too long could be rendered unusable due to the loss in moisture content (Nnfcc, 2016, Dussadee et al., 2016)

4. The carbohydrate content of the feedstock should be within the acceptable range (Jørgensen, 2009) for biogas optimum production or else co-digestion should be considered. It is reported that if the feedstock consists of mainly carbohydrate such as cellulose and hemicellulose the methane yield will be low (Sridevi et al., 2012).

5. The feedstock should have passed the theoretical methane production potential test (Biswas et al., 2007).

3.1.1 Need for biogas development in South Africa

There is significant prospect for biogas production (biomass from agricultural activities) for the generation of electricity in South Africa. At present, South Africa's daily load profile indicates that peak demands occur between 7a.m. - 10 a.m. and 6.p.m – 8 p.m. This is because many South African households use electricity for cooking as well as for heating (specifically during winter) in contrast to the use of gas which is prevalent in Europe and Unites states of America. As a result, there is disparity in efficiently matching the period of peak demand with the period when the peak solar irradiation is available to produce energy. Similarly, wind energy profiles usually do not strongly correlate with this demand profile. Due to the fact that biogas plant can be easily located anywhere feedstock is accessible, it offers a promising alternative for satisfying some part of the load demand in South Africa. The biogas application for electricity generation is specifically appropriate for rural communities in South Africa where feedstock is readily available. As long as a suitable and adequate quantity of feedstock is supplied into the bio-digester, the inadequacies of meeting peak demand in relation to available power is eliminated, and as such, electricity can be generated at any time of the day and when needed. In essence, it can be used in meeting peak energy demand spikes.

The benefits of biogas-driven combined heat and power (CHP) plants outstrip the simple production of heat and power. The prospect for the enhancement of human welfare is important. When adopted for rural electrification, heat, gas for cooking or a combination of these can reduce air pollution, improved lighting and establishment of job opportunities for the locals (Owusu and Asumadu-Sarkodie, 2016). A renewable Independent Power Producer (IPP) procurement programme in South Africa has a target of ensuring the installation of 3725 MW of renewable energy to increase renewable energy penetration in the national energy mix by 2030 (Assessment, 2012). Interestingly, biogas is one of the renewable energy sources incorporated into the 3725 MW of renewable allocation. It is estimated that about 12.5MW of power will be generated through biogas. However, the development and installation of biogas plant in South Africa has been slow with only about 150 biogas digesters in operation at present. Only few of the existing large scale biogas digester available in South Africa are majorly used for solid and hazardous waste from landfills which is in contrast to other developed countries where various feedstock are utilised for larger scale biogas digester (Goemans, 2017). In order to ensure the adoption of biogas in South Africa, it is essential to carry out a preliminary identification and classification of potential feedstock. This will foster the development of a feedstock database which can help in the siting of biogas digesters across the country. This paper therefore presents the identification and characterization of potential feedstock for biogas production in South Africa.

3.1.2 Biogas feedstock and the South African perspective

According to Bond and Templeton (2011) biomass that contains carbohydrates, proteins, fats, cellulose, and hemicellulose as main components can be used as feedstock for biogas production. However, certain factors such as the chemical and physical form of the biomass affects the biodegradability of the feedstock (Lee, 2007). Several types of feedstock have been reported for the production of biogas. These include; agricultural wastes, energy crops, municipal bio-wastes, industrial wastes and wastewater (Figure 3-1) (Steffen et al., 1998). These are further categorized as agricultural-, industrial- and community-based (Table 3-1).

Industrial waste includes the peels of vegetables, stale cooked and uncooked food. Domestic waste is an underexploited substrate for the production of biogas (Rajendran et al., 2012). Vegetable waste has a high sugar content that easily ferments to organic acids. This encourages acidification that results in the inhibition of methanogenic bacteria activities (Scano et al., 2014). In an effort to enhance the production of biogas, co-digestion of domestic waste and another feedstock is recommended. Raw vegetable should be treated physically by chopping them, as methane production is increased by reducing the particle size due to the increase in surface area for microbial activities (Wantanee and Sureelak, 2004). Biogas can be produced from all organic material however, not all of the organic materials are relevant to the South African industry.

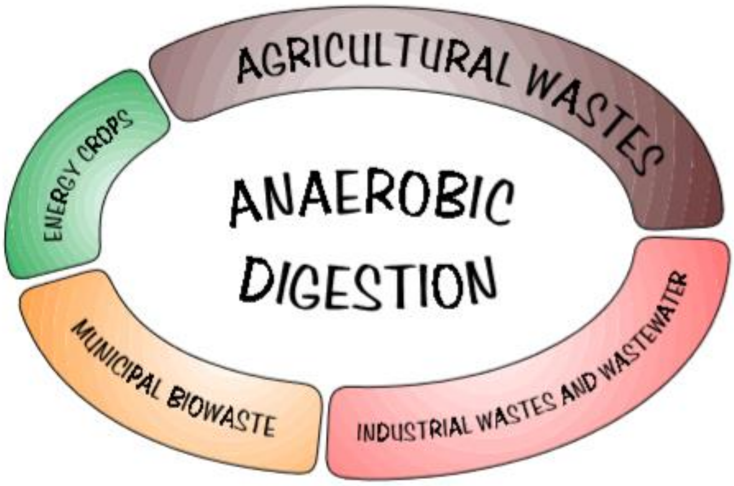


Figure 3-1: Sources of suitable substrates for anaerobic digestion

Table 3-1: Various feedstock from different source (Smith et al., 2011)

Sources	Various Feedstock
Agriculture	• Manure • Energy Crops • Algal Biomass • Harvest remains
Industry	• Food/beverage processing • Dairy • Starch industry (e.g. cassava, corn, wheat and sweet potatoes) • Sugar industry (e.g. sugarcane and sugar beet raw) • Pharmaceutical industry (e.g. Water may be a raw materials) • Cosmetic industry (e.g. raw materials) • Biochemical industry (e.g. crops, woody plants, algae) • Pulp and paper

Sources	Various Feedstock
	• Slaughterhouse/rendering plant
Communities	• OFMSW • MSW • sewage sludge • grass clippings/garden waste • food remains

Several researches have been conducted using typical feedstock animal waste, human excreta/sewage, kitchen/food waste and co-digestion of multiple feedstock for biogas production. Table 3-2 shows typical biogas production potential of some of the feedstock used for domestic bio digesters.

Table 3-2: Biogas production from selected feedstock

Feedstock	Daily Production (kg/animal)	%DM	Biogas Yield (m^3/kg DM)	Biogas Yield (m^3/animal/day)	Reference
Cow Manure	8	16	0.2 – 0.3	0.32	(Bond and Templeton, 2011)
Human excreta	0.5	20	0.35 – 0.8	0.04	
Pig Manure	2	17	0.25 – 0.5	0.128	(Surendra et al., 2014)
Chicken Manure	0.08	25	0.35 – 0.8	0.01	
Food Waste	-	34	0.55	-	
Cow Manure: Human excreta (1:1)	-	18	0.407	-	
Food waste: Human excreta (1:1)	-	27	0.489	-	

3.2 MATERIALS AND METHODS

3.2.1 Potential feedstock available in South Africa for biogas

As much as municipal solid waste and sewage are considered as the highest potential feedstock in South Africa, other agricultural feedstock could be explored for more opportunities. Table 3-3 shows some of the potential feedstock that can be explored in South Africa. South Africa has different temperate zones and these different temperatures enhance the production of fruit, with different varieties distributed throughout the country. The major fruit production is citrus fruits with 2.1 tonnes which is followed by grapes with more than 1.8 tonnes. These fruits can serve as potential feedstock.

Energy crops, such as cassava, are considered to be a traditional agricultural crop grown normally for food. However, due to its high energy characteristics, it has been considered for energy production (López-Bellido et al., 2014). Cassava co-digested with other feedstock could be an alternative substrate for various communities for the production of biogas in South Africa. Since cassava is yet to be listed as a staple food crop in South Arica, cassava, its peels and other by-products from its processing can be suitable for energy production.

Table 3-3: Production volume of feedstock in South Africa (Faostat, 2018)

Group	Feedstock	Total production (Tonnes)
Agriculture	Bananas	371 385.00
	Citrus fruits	2 102 618.00
	Grapes	1 839 030.00
	Apples	790 636.00
	Cassava	Insignificant
	Sugarcane	15 074 610.00
Industry	Fruits and vegetables	559 520.00

3.2.2 Identification of energy crop and bio-waste substrates in Southern Africa

Different feedstock was collected from different sampling procedures. Three (3) different substrates (i.e. cassava tuber, cassava peels, fruits and vegetables and cattle dung) were selected because of their unique properties and their importance in the production of renewable energy through anaerobic digestion. The selected feedstock was collected as follows: cassava samples were collected from a cassava plantation in the Nampula Province of Mozambique. Cattle dung was collected from the Ukulinga Research Farm, Pietermaritzburg, South Africa. Fresh fruit and vegetable residues were obtained from a fruit and vegetable supermarket in Pietermaritzburg, KwaZulu-Natal.

Table 3-4 shows numerous studies conducted on wastes from the South African fruit industry with regards waste to treatment and beneficiation. Various studies on beneficiation and the application of fruit waste as a feedstock for renewable energy generation has been conducted in various studies in South Africa, but co-digestion with other feedstock such as energy crop has been limited, hence the need to explore such research gap.

Table 3-4: Various studies on fruit waste in South Africa

Study Focus	Fruit waste	Outcomes	Reference
Bioremediation and beneficiation application	Pineapple cannery wastewater	Suitable to produce ethanol due to its high carbohydrate content of about 19.8 g/L.	(Prior and Potgieter, 1981, Garcin and Burton, 2007)
Water and wastewater management in fruit- and vegetable-processing plants	Fruits and vegetables	Guideline to minimise water intake and wastage.	(Khan et al., 2015)
Renewable energy	Fruit cannery wastewater	The anaerobic digestion of fruit cannery wastewater for	(Sigge and Britz, 2007)

Study Focus	Fruit waste	Outcomes	Reference
		biogas production through the use of an upflow bioreactor.	
Renewable energy	Various fruit processing Wastes	Potential Energy recovery from fruit waste identified theoretically	(Burton et al., 2009)

3.2.3 Justification of using cattle manure, cassava and fruits and vegetables as co-substrate

It is worth noting that cattle manure, cassava and fruits and vegetables as co-substrate were selected based on the availability and in terms of quantity and the energy production potential. According to Faostat (2018), in 2016, the production of cattle manure is around 136 161 tons per year in South Africa. These large volumes of cattle manure most times end up in landfills or being applied as fertilizer. The use of cattle manure for biogas production provides an alternative option for energy and waste treatment (Abubakar and Ismail, 2012, Scholtz et al., 2013).

Furthermore, according to Hamilton (2014), cattle manure is rich in organic materials and in nutrients for this reason it is often used as an agricultural fertilizer. Several researches has been conducted into the production of biogas from cattle manure by mixing the cattle manure with other organic waste such as households and industrial waste (Maamri and Amrani, 2014, Yohaness). The co-digestion of cow/cattle manure has shown to play an important role in the anaerobic digestion process which has resulted in several environmental and economic benefits (Hassan et al., 2015). Girija et al. (2013) conducted an analysis on the microbiota of cattle manure, from this research analysis it was discovered that the following bacteria were found in the cattle manure Bacteroidetes (38.3%), Firmicutes (29.8%), Proteobacteria (21.3%) and Verrucommicrobia (2%). These bacteria are responsible for the degrader of complex organic matter in the form of lignocelluloses, chitin, cellulose, xylose and xylem (Martens et al., 2009). For this reason the use of cattle manure is justified as inoculum and also as co-digester in the anaerobic process.

The production of cassava in the world is about 263 million tons per annum with South Africa having an insignificant data on the production and consumption available (Faostat, 2018). While cassava has had a long history in the rest of Africa, cassava is not a well-known crop in South Africa because cassava is not yet considered a staple food in the country. It will therefore be interesting to explore its energy production potentials in South Africa. Cassava usually survives and produces better harvests in locations where maize and other energy crops will not grow or yield bountifully. It is drought tolerant and can survive in extreme weather, climatic conditions and soil with low nutrients. Since cassava succeeds in drought conditions, it therefore requires low agro-chemical inputs (Okudoh et al., 2014).

It however yields well to irrigation or in regions with higher rainfall. Cassava is extremely flexible in its management requirements and has the potential of high-energy production per unit area of land. Because cassava has no definite maturation point, harvesting may be delayed until market, processing or other conditions are more favorable. This flexibility means cassava may be field stored for several months or more. Based on these features of cassava, its growth and survival is guaranteed in South Africa if adequate resources are invested.

Since cassava can both serve as energy crop and food, the use of cassava peel (waste) instead of the peeled tuber (food) is suggested in this study. Alternatively, energy crops can be grown on marginal land (landfills) as a capping for landfill (Figure 3-2). Therefore, making the crop unsuitable for food crop production. The latter is proposed here due to the fact that in South Africa some landfills are at the stage of being decommissioned. This creates the land for the capping of landfill through the use of cassava. Though the production of cassava is lacking in South Africa, using cassava as capping crop for landfill would enable its application for energy generation after harvesting. This is because the landfill capping crop has low biodiversity and economic value as there is a high risk of the cassava absorbing toxic trace elements that could present health risks for humans (Whiting et al., 2004, Hutchings et al., 2001). Cassava biomass has many benefits since it contains large amount of fermentable sugar (Okudoh et al., 2014).

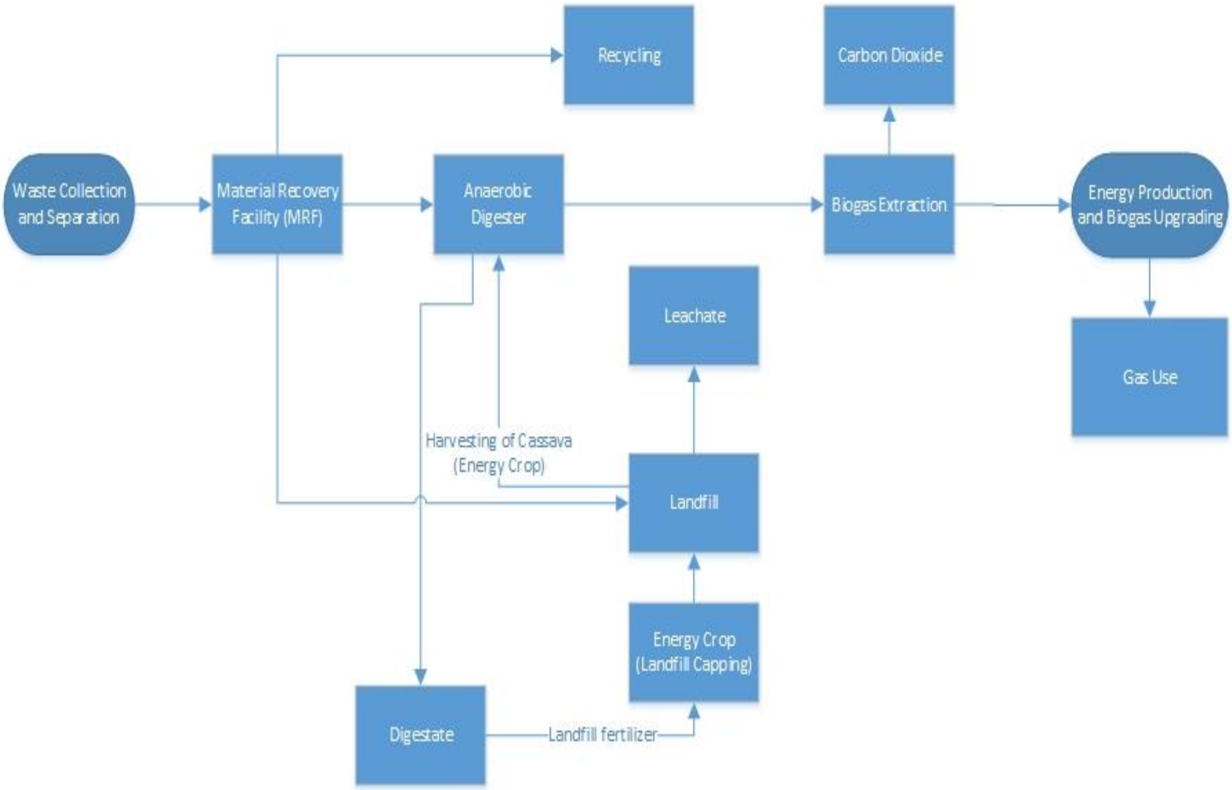


Figure 3-2: Integration of energy crops and waste into landfill operation for biogas production

3.3 METHOD FOR SAMPLING, PREPARATION AND CHARACTERIZATION OF FEEDSTOCK

3.3.1 Sampling method and preparation of feedstock

In an effort to obtain a more homogenous sample, the substrates were thoroughly mixed, after which each pile was then divided into four parts. Two diagonally opposite quarters were mixed, while the other two diagonally opposite quarters were removed or discarded (Figure 3-3). The mixed diagonals were again divided into four parts. This procedure was repeated until a small sample has been extracted. The above procedure was followed for all the substrates.

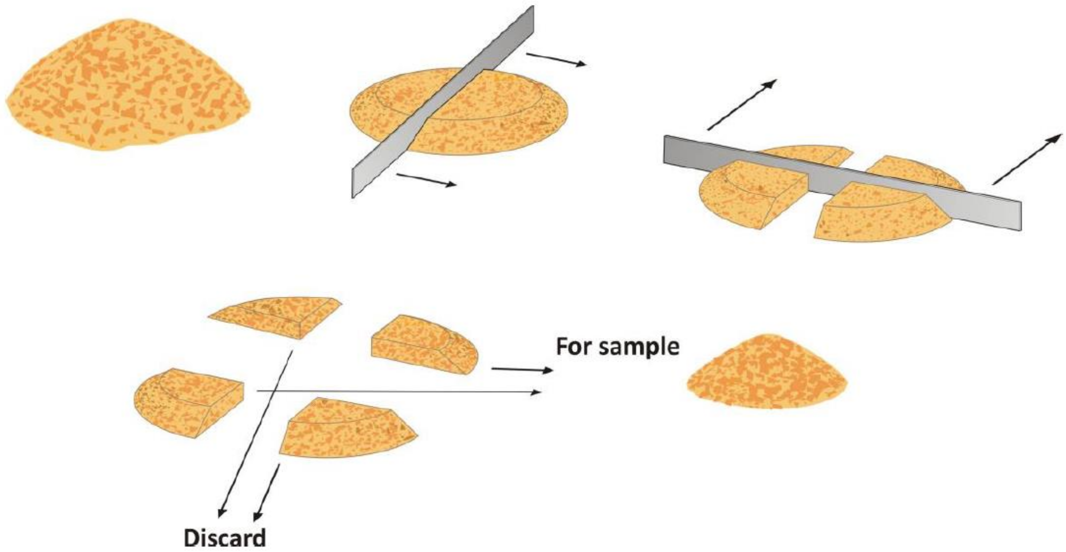


Figure 3-3: The coning and quartering method (Alakangas, 2015)

The preparation of the potential feedstock was performed following the outline protocol below:

Cassava

Varieties of cassava are grown in Mozambique based on the regions. The *Munhaca* variety most common in Southern region, *Inicriano* and *Bedo* in the Central Region, and *Nikwaha*, *Tomo* and *Cororo* varieties in the Northern region. The cassava types can be grouped into two major types namely: sweet and bitter (Silici et al., 2015). The cassava (*Manihot esculenta Crantz*) samples were collected in such a way that it covered random different parts of the entire volume. These sub-samples were mixed together. Coning and quartering were used to reduce the size of the mixed samples. One hundred kilogrammes of the collected fresh cassava tuber was mechanically pre-treated by peeling, while the remaining 100 kg of the fresh cassava was not peeled. Both the peeled and unpeeled cassava were washed with tap water with a pH of 7 and chopped into pieces of about 1 cm^3. Thereafter it was dried in sunlight for two days (Figure 3-3). All prepared feedstocks were stored in a refrigerator at 4 ˚C. The dried cassava tuber was milled with a scientific RSA hammer mill that is equipped with a 2 mm sieve mesh to obtain cassava flour. This is because smaller particles does not only increase biogas production rate but also affects the hydraulic retention rate (Mshandete et al., 2006, Karp et al., 2013).

Cattle dung

To form a cattle dung slurry, fresh cattle dung (CD) was mixed with water (W) to a ratio of 1:2 (CD:W) (Biswas et al., 2012). The slurry inoculum was filtered by passing it through a 0.5 mm diameter sieve to separate the solid content from the slurry, after which it was kept in a container at 4 °C.

Fruit and vegetable residue

Fresh fruit and vegetable residues were sampled randomly. The samples were then oven-dried at 60 °C until they reached a constant weight. The sample size was reduced to < 1mm through milling. Equipment combination of a TRF 400 hammer mill and a laboratory blender were used for size reduction. The fruits used in this experiment were mainly banana, which were analysed as the fruit only (peeled banana). The sample was stored in plastic sample bags in the refrigerator at 4 °C before analysis. This is to ensure that the condition of feedstock remains unchanged to avoid obtaining flawed results (Assegid, 2014).

3.3.2 Feedstock composition and physicochemical characterization

The feedstock sample was characterized in terms of the proximate and ultimate analysis. The proximate analysis refers to the physiochemical features in terms of its moisture content, total solids, volatile solid, pH value, total nitrogen, total carbon and ash. On the other hand, the ultimate analysis refers to the elemental carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulphur (S) compositions in the feedstock under consideration. The main purpose for conducting the characterization tests is to determine and understand the physical and chemical characteristics of the substrates that are being used, thereby creating a reference point for the experiments. This will assist in accessing how effective the substrate is in the production of biogas.

The analyses were conducted on the individual feedstock (cassava tuber, cassava peel, fruits and vegetable and cattle dung) using the American Standard Methods for Examination of Water and Wastewater (ASTM). Tests were repeated in triplicate for accuracy and repeatability (Eaton et al., 2005).

Moisture content (MC)

The ratio of the mass of water to the total mass of the sample is defined as moisture content. MC can be illustrated by the following Equation 3-1:

$$MC(\%) = \frac{Mass\ of\ wet\ sample\ -\ Mass\ of\ dry\ sample}{Mass\ of\ wet\ sample} x\ 100 \qquad (3\text{-}1)$$

The procedure used to measure the moisture content is as follows: Approximately 100 g of solid sample (each substrate) was weighed into crucibles at room temperature, after which it was placed into the oven at 105 ℃ for 24 hours. Thereafter the heated samples were placed in desiccators to cool down. The desiccator contains silica gel underneath as illustrated in Figure 3-4. The silica gel inside the desiccators absorbs any moisture that is present. The desiccators are moisture free. After cooling down the sample to obtain the mass of the dry sample, the cooled down sample is weighed again. Thereafter the moisture content is calculated using Equation 3-1.

Figure 3-4: (a) Crucibles in oven at 105℃, (b) Crucibles in desiccator to cool down

Total solids (TS)

Total solids (TS) is the measurement that represents the quantity of total solid residue that remains after the sample has been oven dried at 105℃ for 24 hours. The test is conducted in accordance with the Standard Method for the Examination of Wastewater by Eaton *et al.* (2005) no. 2540 G, D and it is calculated using Equation 3-2.

$$\text{Total Solids } (\%) = \frac{\text{Mass of dry sample}}{\text{Mass of total sample}} \text{ x } 100 \qquad (3\text{-}2)$$

Volatile solids (VS)

The residue from the TS test is placed in the furnace (Figure 3-5), which is fired / ignited at 550 ℃ for 2 hours to calculate the VS. Before placing the residue in the furnace, it is pre-heated to 550 ℃. The total VS test is used to determine the quantity of organic matter in the sample (Eaton *et al.*, 2005). The tests were conducted in accordance with the Standard Method of Examination of Wastewater and Water-no. 2540 G (Eaton *et al.*, 2005) and the total Volatile Solids were calculated using Equation 3-3.

$$\text{Total Volatile Solids}(\%) = \frac{\text{Mass of dry sample} - \text{Mass of sample fired in furnace}}{\text{Mass of total sample}} \text{ x } 100 \qquad (3\text{-}3)$$

Figure 3-5: Crucibles in furnace at 550℃

pH

The acidity or alkalinity in a solution is measured by a pH test. The test was conducted in the slurry before the use of the substrate for anaerobic digestion using a Labotec Orion Model 410A pH metre as illustrated in Figure 3-6. The measurement of the pH of the substrate is essential to determine if the pH level of the substrate is within the required range for the production of biogas. Before using the pH metre, it was first calibrated to a pH range of 4–10. The probe was dipped into the sample to obtain the pH readings.

Figure 3-6: Orion Model 410A pH metre

3.3.3 Mathematical models for determination of theoretical methane production

According to Labatut et al. (2011), there are several theoretical approaches to estimate the Biochemical Methane Potential (BMP) of a feedstock or substrate. This is based on the assumption that the substrate will completely degrade and that the microorganisms in the substrate does not use energy (Forgács, 2012). This method relies on the accuracy of the data of substrate composition, therefore it cannot represent a realistic representation of BMP which is often higher than that of the observed methane (Forgács, 2012, Labatut et al., 2011). Some of the theoretical BMP used to estimate the maximum methane are as follow:

1. Elemental composition: if the elemental composition (ultimate analysis) of the waste material/substrate is known,

2. Substrate nutrient composition: assuming the organic waste comprises of carbohydrates, proteins and lipids.

Theoretical methane production potential from substrate elemental composition

The ultimate analysis results of the selected feedstock are presented in Table 3-6 & Table 3-7. The elemental composition was used, according to Franco et al. (2007), to estimate the maximum theoretical biogas and methane yield using Buswell's equation (Equation 3-4) to calculate the theoretical methane yield (Buswell and Neave, 1930). The general molecular formula can be presented to be of the form $\mathrm{C_aH_bO_cN_d}$.

$$\mathrm{C_aH_bO_cN_d} + \left(\mathrm{a} - \frac{\mathrm{b}}{4} - \frac{\mathrm{c}}{2} + \frac{3\mathrm{d}}{4}\right)\mathrm{H_2O} \rightarrow \left(\frac{4\mathrm{a}+\mathrm{b}-2\mathrm{c}-3\mathrm{d}}{8}\right)\mathrm{CH_4} + \left(\frac{4\mathrm{a}-\mathrm{b}+2\mathrm{c}+3\mathrm{d}}{8}\right)\mathrm{CO_2} + \mathrm{dNH_3} \qquad (3\text{-}4)$$

Equation 3-4 above represents the degradation of carbon in the substrate under consideration. The coefficients a, b, c, and d are dimensionless coefficients and can be evaluated from the approximated ratio of each component number of moles to the minimum number of moles among all the components (Roati et al., 2012, Jingura and Kamusoko, 2017), where:

$$a = \frac{\frac{\%C}{Molar\ Mass\ C}}{L},\ b = \frac{\frac{\%H}{Molar\ Mass\ H}}{L},\ c = \frac{\frac{\%O}{Molar\ Mass\ O}}{L},\ d = \frac{\frac{\%N}{Molar\ Mass\ N}}{L},\ \text{and}\ L = \frac{\%M}{Molar\ Mass\ M}$$

%C, %H, %O and %N represent the composition of C, H, O and N in the organic substrate respectively.

M represents the element with the minimum number of moles in a given sample, and in most cases, *M* is usually nitrogen, such that the value of *d* is almost always equal to1. Molar Mass C is the molar mass of carbon, and the same applies for hydrogen (H), oxygen (O) and nitrogen (N).

The maximum theoretical biogas production (B_{th}) and the theoretical methane production (M_{th}) can be estimated from Equations 3-5 and 3-6 respectively.

$$B_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{a22.415}{12a+b+16c+14d} \quad (3\text{-}5)$$

$$M_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{\left(\frac{4a+b-2c-3d}{8}\right)22.415}{12a+b+16c+14d} \quad (3\text{-}6)$$

The Buswell equation (Roati et al., 2012) was further used to verify the selected promising substrates for further examination in the laboratory and in a pilot scale test.

3.4 RESULTS AND DISCUSSION

3.4.1 Identified biogas production biomass

Cassava tuber, cassava peels, cattle dung, fruits (Banana) and vegetable residues were selected for this study. Figure 3-7 (A – E) shows pictures of selected biomass for this study.

Figure 3-7: (A) Unpeeled cassava tuber, (B) Cassava peel, (C) Cattle dung, (D) Vegetable and (E) Fruit

3.4.2 Proximate and ultimate analysis results

Table 3-5 shows the results of proximate and ultimate analysis of all the selected feedstock for anaerobic digestion. All the feedstocks (cassava tuber, cassava peels, fruits & vegetables and cattle dung) were characterized and the results show some differences in most of the properties as shown in Table 3-5.

Table 3-5: Physical and chemical characteristics of cassava tuber, cassava peels, fruit & vegetable waste and cattle dung

Characterization	Biomass			
	Cassava tuber	Cassava peel	Fruit & vegetable waste	Cattle dung
Moisture content (%)	61.58 ± 2.11	79.68 ± 0.01	58.40 ± 0.1	83.50 ± 0.4
Total solids (%)	42.25 ± 1.51	20.32 ± 0.12	41.60 ± 1.2	19.84 ± 0.3
Volatile solids (%)	91.27 ± 0.52	75.51 ± 1.01	76.10 ± 0.3	12.40 ± 1.5
Starch (%)	76.32 ± 2.01	61.42 ± 0.21	ND	ND
Sugars	77.54 ± 1.11	78.74 ± 1.07	42.87 ± 1.01	ND
pH	6.87 ± 0.47	6.94 ± 0.24	7.34 ± 0.15	6.57 ± 0.11
Protein (g)	1.01 ± 0.01	1.11 ± 0.11	77.30 ± 0.67	-
Total nitrogen (%)	0.53 ± 0.44	0.87 ± 0.14	0.52 ± 0.34	2.06 ± 0.2
Total carbon (%)	39.67 ± 1.78	51.91 ± 0.01	39.06 ± 0.11	43.12 ± 0.7
C:N	74.84:1	59.67:1	75.12:1	18.50:1
Ash (%)	3.06 ± 0.66	4.98 ± 0.31	9.44 ± 0.11	1.66 ± 0.21
Phosphorus (%)	0.16 ± 0.57	0.20 ± 1.21	ND	0.42 ± 0.04
Fe (mg/kg)	62.00 ± 0.17	201.09 ± 0.51	ND	ND
Zn (mg/kg)	15.01 ± 0.12	25.10 ± 1.17	ND	ND
Mn (mg/kg)	8.02 ± 1.21	36.45 ± 0.55	ND	ND

ND: Not determined

From the Table 3-5 above it can be observed that a major difference in the moisture content with cattle dung having the most moisture content at 83.50%. The cassava peels showed lower starch content (61%) compared to that of the cassava tuber with 76%. However, the cassava peels reported a higher fermentable sugar of 79%, which is higher than that of the cassava tubers by 1.5%.

The cassava peel showed high traces of heavy metals, namely Zn, Mn and Fe (25.10 mg/kg, 36.45 mg/kg and 201.09 mg/kg) compared to that of cassava tuber. According to Hoban and Berg (1979), traces of Fe is essential to the fermentation of methane.

The carbon-to-nitrogen ratio of a feedstock is represented by C/N. For a feedstock to produce optimal gas, the C/N ratio among other factors plays an important role. A feedstock with a ratio 25:1 of C/N produces an optimum gas (Gerardi, 2003). According to Kwietniewska and Tys (2014), for optimum performance of the AD the feedstock should have a C/N ratio of 20:1 – 30:1. It can be observed that all the selected feedstock have a C/N ratio of greater than 30:1, which could cause rapid depletion of nitrogen and as a result cause lower production of gas (Khalid et al., 2011), with the exception of cattle dung, which is within the range. In order to mitigate the C/N ratio outside of the range, co-digestion could be considered (Hartmann et al., 2002). However, the correct combination of other parameters (pH, biodegradable organic matter and toxic compounds) in the co-substrate mixture is important. To increase the biogas yield co-substrates in the digester with carbon rich substrates such as energy crop would be favourable (Pavan et al., 2007). Cassava tuber and cassava peels were found to be rich in carbohydrates with sugar content of approximately 78%, which is good indication of cassava potential as it is well recorded that high biogas yields are usually related to the high carbohydrate (Achinas et al., 2017). Carbohydrates in cattle manure could not be determined due to complexity as the substrate is composed of carbohydrates, proteins and fats, while the carbohydrates in Fruits and vegetables largely contain carbohydrates and a relatively less amount of proteins and fats.

According to Christy et al. (2014), the different stages of the AD process requires different optimal pH value (Hydrolysis Stage pH 4, Acidogenisis Stage pH 6.5, Acetogensis stage pH 6.0 and Methanogenesis stage pH 6.5 – 7.8). The selected substrates (Table 4) have a pH within the acceptable range of 6.5 and 7.8 for the AD process to perform well (Okonkwo et al., 2013). Cattle manure is an easy choice of feedstock because of its neutral pH and its resistance to change in pH. However, it has low energy because of its pre-digestion in the gastrointestinal (Meshach, 2013).

3.4.3 Theoretical methane production potential from substrate elemental composition

For all the selected feedstock (cassava, cattle manure, and fruit & vegetable waste), the ultimate analysis (elemental composition) was performed. Equation 3-5 & 3-6 was used to estimate the ultimate methane in order to investigate the potential of the feedstock selected. Mono-digestion were conducted, the results obtained are shown in Table 3-6.

Table 3-6: Mathematical ultimate methane yield of different substrates using elemental analysis

Sample	Elemental analysis					C, H, O, N coefficients				Molecular formula	$B_{th}\left[\frac{m^3}{kg_{vs}}\right]$	$M_{th}\left[\frac{m^3}{kg_{vs}}\right]$
	pH	N	C	H	O	A	b	c	d			
CP	7.07	0.87	51.91	5.90	41.79	69.61	94.94	42.03	1	$C_{70}H_{95}O_{42}N$	0.965	0.496
CM	6.62	1.38	22.50	3.29	14.90	19.02	33.38	9.45	1	$C_{20}H_{34}O_{10}N$	0.999	0.575
CT	6.6	1.75	53.29	5.93	41.16	35.53	47.44	20.58	1	$C_{31}H_{36}O_{21}N$	0.975	0.499
F & V	6.62	2.17	39.49	5.85	30.16	21.23	37.74	12.16	1	$C_{30}H_{21}O_{12}N$	0.949	0.533

F & V: Fruits and Vegetable waste; CP: Cassava Peel; CT: Cassava Tuber; CM: Cattle Manure

The results in Table 3-6 shows that the cattle manure obtained the highest ultimate methane yield (0.575 m^3/kg VS), whereas the lowest methane yield (0.495 m^3/kg VS) was obtained from cassava peels. This result indicates that the selected feedstock has a potential of producing biogas.

Numerous studies has shown that co-digestion is a promising way of improving the performance of AD (Zhang et al., 2014). The elemental analysis is used to calculate the ultimate methane yield of co-digested substrates at different ratios (Table 3-7) (Gerber and Span, 2008, Biswas et al., 2007). From Table 3-7, it can be noted that co-digesting CT with F&V improved the biogas and methane yield which is in agreement with the literature that indicate that improvement of biogas yield could be done by co-digestion of two or more substrates at the correct ratio. This may assist in establishing the methane potential of the substrate at different substrate ratio which can thereafter be investigated further through experimental process.

Table 3-7: Mathematical ultimate methane yield of different co-digestion ratio using elemental analysis

Sample	Elemental analysis					Molecular formula	$B_{th}\left[\frac{m^3}{kg_{vs}}\right]$	$M_{th}\left[\frac{m^3}{kg_{vs}}\right]$
	pH	N	C	H	O			
CM:CP (20:80)	7.07	1.35	52.03	6.26	40.36	$C_{45.01}H_{65.00}O_{26.18}N$	0.971	0.512
CM:CP (40:60)	6.62	1.83	52.39	6.65	39.12	$C_{33.37}H_{50.84}O_{18.69}N$	0.979	0.528
CM:CP (50:50)	6.62	2.07	52.57	6.85	38.51	$C_{29.59}H_{46.23}O_{16.25}N$	0.982	0.536
CM:CP (60:40)	6.62	2.31	52.76	7.04	37.89	$C_{26.59}H_{42.59}O_{14.32}N$	0.985	0.543
CM:CP (80:20)	6.62	2.80	53.12	7.43	36.65	$C_{22.15}H_{37.19}O_{11.46}N$	0.992	0.559
CT:FV (20:80)	7.07	2.58	51.11	7.19	39.13	$C_{23.13}H_{39.03}O_{13.28}N$	0.954	0.526
CT:FV (40:60)	6.62	2.36	51.38	6.84	39.42	$C_{25.38}H_{40.56}O_{14.60}N$	0.960	0.519
CT:FV (50:50)	6.62	2.25	51.51	6.67	39.57	$C_{26.67}H_{41.42}O_{15.36}N$	0.962	0.516
CT:FV (60:40)	6.62	2.14	51.65	6.50	39.71	$C_{28.08}H_{42.39}O_{16.20}N$	0.964	0.512
CT:FV (80:20)	6.62	1.92	51.91	6.15	40.01	$C_{31.39}H_{44.63}O_{18.14}N$	0.970	0.505

F & V: Fruits and Vegetable waste; CP: Cassava Peel; CT: Cassava Tuber; CM: Cattle Manure

3.5 CONCLUSION

This paper presents the identification and characterization of potential feedstock for biogas production in South Africa. Using American Standard Methods for Examination of Water and Wastewater (ASTM) method, the pH, total solids (TS), volatile solids (VS), total carbon and total nitrogen were determined with proximate and ultimate analysis of the feedstocks. The conclusions drawn from the results obtained are as follows:

The large amount of carbohydrate, total solids (TS), volatile solid (VS) and the low fibre in the cassava biomass indicates high biogas production potential. However, the carbon to nitrogen ratio (C:N) of cassava tuber and cassava peels 74.84:1 and 59.67:1 respectively which is higher than normal and may have to be co-digested with animal manure such as cattle manure to bring the C:N ratio to about 20:1;

The benefit of using cassava biomass for future crop-based biogas plants is that it reduces the need to use lands available for food production and artificial fertilizers as they can be cultivated in degraded lands such as landfills.

Analysis of the theoretical methane production potential from substrate elemental composition has shown that the highest methane yield was achieved from cattle manure (0.575 m^3/kg VS) while the lowest methane yield (0.495 m^3/kg VS) was obtained from cassava peels.

The mathematical ultimate methane yield of fruit and vegetable using elemental analysis showed a much higher methane yield (0.533 m^3/kg VS) compared to cassava tuber and cassava peels 0.499 m^3/kg VS and 0.496 m^3/kg VS respectively.

This study thus shows that cassava (tuber and peels), fruit and vegetable wastes are potential sources for energy production. Further study will focus on ascertaining the biogas yield under mesophilic temperature with varying co-digestion ratios and taking into consideration the factors that affects the maximum yield.

CHAPTER 4:
CO-DIGESTION OF ANIMAL MANURE AND CASSAVA PEEL FOR BIOGAS PRODUCTION IN SOUTH AFRICA

Nathaniel Sawyerr[1]*, Cristina Trois[2], Tilahun Workneh[3], Vincent Okudoh[4]

[1,2] Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

[3] Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

[4] Department of Biotechnology and Consumer Sciences, Cape Peninsula University of Technology, Cape Town Campus, South Africa.

PREAMBLE

Based on the identified feedstock in chapter 3 and the promising theoretical results, further investigation was conducted on the biogas yield of co-digestion of animal manure and cassava peels. Chapter 3 aims to define the optimum weight ratio for co-digestion between animal manure and cassava peels (100:0, 0:100, 80:20 and 20:80, % w/w CM:CP) for optimum biogas yield in anaerobic conditions. It thereafter presents a comparative evaluation of the experimental and theoretical yields. An assessment of the effect of the different CM ratios on the biogas yield is also presented.

This chapter has been accepted and presented as a conference paper, and published in the conference proceedings of the 9th International Conference on Advances in Science, Engineering, Technology & Waste Management (ASETWM-17), held in Parys, South Africa on 27-28 November 2017. The copy of the original presented article is in Appendix P3 as indicated in the declaration section.

https://doi.org/10.17758/EARES.EAP1117059

Received 16 August 2017; Accepted 25 August 2017, EARES.EAP1117059/

ABSTRACT

Global energy demand is on the rise due to continuous increases in population, economic growth, and energy usage. Several studies have been done on biogas, but in South Africa, these are biased toward industrial wastewater. Therefore, there is a need to explore other alternatives for biogas generation, for example energy crops such as fodder beets and cassava, on which studies are limited. Cassava has several advantages compared to other crops, including the ability to grow on degraded land and where soil fertility is low. It also has the highest yield of carbohydrate per hectare (4.742 kg/carb) apart from sugarcane and sugar beet, which makes it suitable for bioenergy (biogas) generation. This study was designed to determine the performance of co-digestion of cassava peel with cattle manure in different ratios, and to study the effect of the mixed ratios on methane yield through batch anaerobic digestion. All digesters were run simultaneously under mesophilic temperatures of 35 ± 1 °C. The digestion was carried out in 600 mL SCHOTT DURAN® glass laboratory bottles. The results showed that co-digestion influenced biogas production and methane yield. The final cumulative methane yields by the co-digestion of CM and CP at the CM:CP mixing ratios of 80:20 and 20:80 were 738.76 mL and 838.70 mL respectively. The corresponding average daily methane yields were 18.42 mL/day and 20.97 mL/day. This study thus suggests that methane production could be enhanced using CP in a co-digestion process and at a 20:80 CM:CP ratio.

KEYWORDS: Cassava, Biogas, Co-digestion, Biomass, Animal Manure

4.1 INTRODUCTION

Biogas technology offers a long-term sustainable renewable energy alternative with the potential to address economic, environmental, and social concerns relating to global development (Sahoo, 2016). Anaerobic fermentation of biomass is a well-developed and efficiently applied process for methane gas production (Verma et al., 2007, Heeg et al., 2014), from the recycling of various organic wastes under anaerobic conditions (Tuesorn et al., 2013, Bożym et al., 2015). Feedstocks used for biogas production include plant waste, animal waste, food waste, municipal sewage sludge, and paper waste (Bożym et al., 2015). However, the quality and quantity of methane yielded and biogas produced largely depends on feedstock characteristics and digester operating conditions, including hydraulic retention time, pH, carbon-nitrogen (C/N) ratio, and inoculum (Verma et al., 2007). Therefore, improving the efficiency of biogas production requires improving the characteristics of the feedstock and operating conditions of the digester. It is also well established that co-digestion of two or more feedstocks produces a higher methane yield than a single feedstock (Panyadee et al., 2013, Haider et al., 2015). Co-digestion is the process of mixing two or more substrates and digesting them simultaneously. The function of co-digestion during AD includes balancing nutrients (C/N ratio, micro- and macro-nutrients), pH regulation, and dilution of inhibitors/toxic compounds (Haider et al. 2015; Bożym et al. 2015; Zhu et al. 2014). These highlight the fact that co-digestion could be a simpler method to improve the feedstock characteristics and digester operating conditions. Some of the major benefits of anaerobic co-digestion over mono-digestion include increased biogas production and methane concentration (Brown and Li, 2012, Mel et al., 2015).

Co-digestion has been utilized extensively to improve the efficiency of biogas production. Its efficiency may be influenced by parameters such as nutrients, feedstock pH, temperature, feed flow rate (loading rate), feedstock type, mixture ratio, and retention time. However, these factors may slow or stall the process of biogas production if their values are not within a certain range. Therefore, understanding the importance and optimal operating conditions for each parameter during AD will contribute to the realization of optimal hydrolyses and digestion (Comino et al., 2012).

The improvement of biogas production via co-digestion requires careful selection of feedstocks (Zhu et al., 2014). In addition, the characteristics and availability of each feedstock plays a key role in improving the efficiency of AD. Co-digestion with a mixture of two or more substrates is considered a more appropriate cost-effective method than pre-treatment, especially when trying to improve the efficiency of plant residues in biogas production. This is because the addition of nitrogen-rich substrates such as animal manure/slurries helps in balancing the C/N ratio of carbon-rich plant residues (Ye et al., 2013, Wei et al., 2014). Research has shown that co-digestion of energy crop residue with a nitrogen-rich substrate can mitigate the rapid acidification of the digester by the high lignin content of plant residue, ease the utilization of energy crops by microorganisms and improve biogas production and methane yield. (Haider et al., 2015). Therefore, this study aims to evaluate the co-digestion of cassava peel and cattle manure at different ratios and the effect of the mixing ratios on methane yield (Okudoh et al., 2014).

The main research highlights of this paper relate to:

- collecting data on co-digestion of cassava peel with cattle manure;
- comparing data on biogas yield from mono-digestion and co-digestion of feedstock;
- Estimating the theoretical biogas yield obtained from the CM:CP co-digestion ratio and comparing the result with the yield obtained from the experimental study.

4.2 MATERIALS AND METHODS

The study was divided into two stages, namely (i) assessing the mono-digestion and co-digestion of the substrates by testing in biochemical methane potential (BMP) reactors at a mesophilic temperature (36 °C) using CM and CP, and using mathematical models to determine theoretical methane production using the elemental composition of the feedstock (Lehtomaki, 2006).

4.2.1 Collection and preparation of substrates for biogas production

The substrates tested in the BMP reactors were CM (animal biomass) and CP (plant biomass). The animal biomass used for this study was collected in a large clean plastic container from Ukulinga Research Farm at the University of KwaZulu-Natal, Pietermaritzburg, South Africa, while the energy crop biomass (Snyman and Botha) was imported from Nampula Province, Mozambique. The CP was sourced from Mozambique because it is more readily available there compared to South Africa (Okudoh et al., 2014). The characteristics of the substrates used are presented in Table 4-2.

The CPs were prepared from fresh cassava roots, which were peeled mechanically with a sharp knife (Figure 4-1A). The CPs (Figure 4-1B) were thereafter washed three times in tap water and allowed to drain for about 30 min. Subsequently, the CPs were sun dried for two consecutive days to reduce their cyanide content (Igwe, 2014). The CM was homogenized using a hammer mill (SER No. 400, Scientific South African,

South Africa) and a laboratory blender to reduce the particle size to less than 5.0 mm (Figure 4-1C) (Oparaku et al., 2013, Promphiphak and Wongwuttanasatian, 2012). The CPs were shredded into smaller sizes. About 20 kg of CP was soaked in water for one month at ambient temperature (35 °C) to soften the substrate and ensure that the microorganisms involved in AD could feed easily on bacteria to produce the biogas. Both the homogenized CM and prepared CP were stored in a refrigerator at 4 °C. The soft CP was made into a slurry by adding water, as shown in
Table 4-1. A flowchart indicating the steps used in the process of biogas production from cassava peels is shown in Figure 4-2.

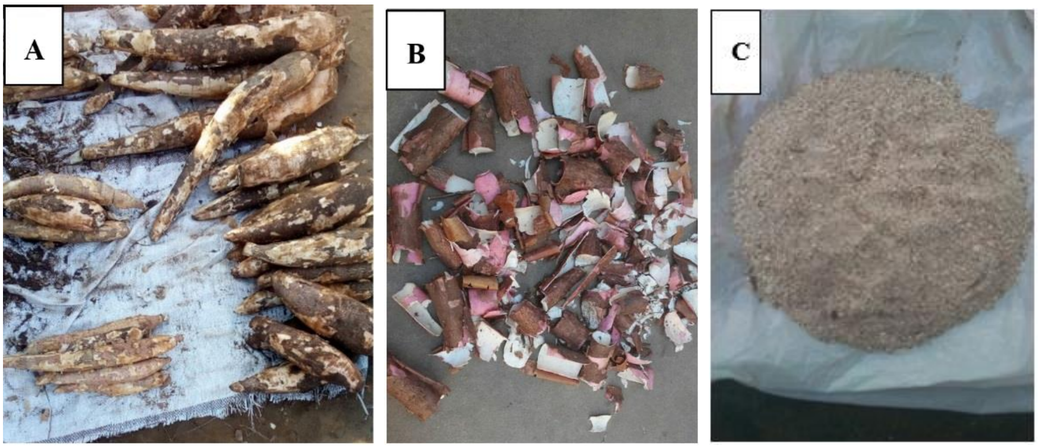


Figure 4-1: (A) Unpeeled cassava roots, (B) cassava peels, and (C) blended cassava peels

Fresh cattle dung (FCD) collected from Ukulinga Research Farm was used as an inoculum to start-up the experiment. This was prepared by mixing FCD with deionized water in a 1:1 ratio (100 g cattle dung:100 mL water). The inoculum was kept in an airtight container at 4 °C; prior to use, it was acclimated and degassed at 35 °C for three weeks to minimize the production of methane from the inoculum (Li et al., 2013). The characteristics of the substrates used in this study (i.e. CM and CP) are shown in Table 4-2.

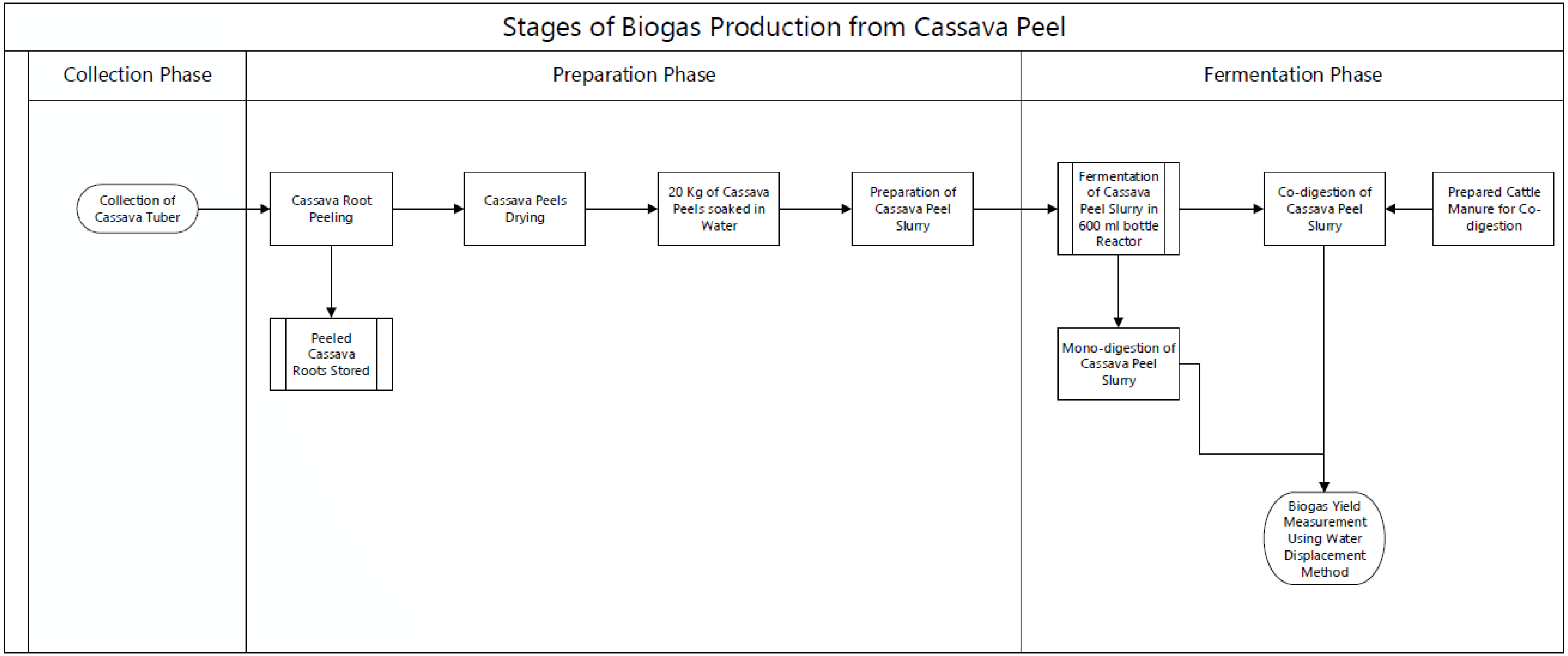


Figure 4-2: Flow chart showing the steps used to prepare cassava used for biogas production

4.2.2 Experimental design

The BMP was studied by investigating the co-digestion of CM and CP. Four co-digestion ratios were investigated: CM:CP = 100:0, CM:CP = 0:100, CM:CP = 80:20, and CM:CP = 20:80. These ratios were based on the volatile solids content, and 1.5 g VS/100 mL of slurry was used in each bottle. Three runs of the experiment were conducted using 600 mL SCHOTT DURAN® laboratory glass bottles as the batch reactor. The experiments were conducted under mesophilic conditions with a temperature of 36 °C. The experimental design shown in

Table 4-1 was used for all three runs. Substrate and deionized water were added to each reactor bottle to produce an effective solution of 1.5 g VS/100 mL. Organic loading was used to avoid acidification while simultaneously ensuring manageable gas volumes (Hansen *et al.*, 2004). The headspace in all the reactor bottles was kept at 20 mL (working volume of 580 mL) and the bio-digesters were flushed with nitrogen gas to set anaerobic conditions.

An inoculum comprising a mixture of 100 g raw (fresh) cattle dung and 100 mL deionized water was prepared. Additionally, 100 g of the raw CM was mixed with 100 mL of tap water and fed to the same anaerobic bio-digester. The slurry was inoculated with the prepared FCD to a ratio of 1:2 w/w. The same method was used to prepare the CP feedstock. The biogas produced was measured using the displacement method. The cumulative biogas volume was thereafter calculated and corrected to standard pressure (760 mm Hg) and temperature (0 °C). Sodium hydroxide (NaOH) was put into the inverted displacement bottle to absorb CO_2 biogas produced in the reactor. It can therefore be assumed that the gas collected in the headspace of the inverted displacement bottle was mainly methane, so that the liquid volume displaced and collected in the measuring cylinder indicated the volume of methane produced (Figure 4-3). The methane produced was measured daily.

Table 4-1: Biochemical methane potential experimental design

Co-digestion	Ratio	Mass of CM (g)	Mass of CP (g)	VS (g)	Solution volume (mL)	Loading (g VS/100 mL)
CM:CP	100:0	20.11	0	8.7	580	1.5
CM:CP	0:100	0	10.37	8.7	580	1.5
CM:CP	80:20	16.09	2.07	8.7	580	1.5
CM:CP	20:80	4.02	8.29	8.7	580	1.5

4.2.3 Biochemical methane potential (BMP) apparatus setup

The BMP experiment was carried out in 600 ml SCHOTT DURAN® glass laboratory bottles (bio-digesters) operated in a batch system (Figure 3). The bio-digester bottles were plugged with tight rubber plugs equipped with valve for biogas measurement. The bio-digester was operated at a controlled temperature of 35 ± 1 °C using a thermostatically controlled electricity heated water bath. The biogas that formed inside the bio-digester was measured using the liquid displacement method as indicated in Figure 4-3 (Jingura and Matengaifa, 2009). The schematic diagram of experimental laboratory was set up as shown in Figure 10.

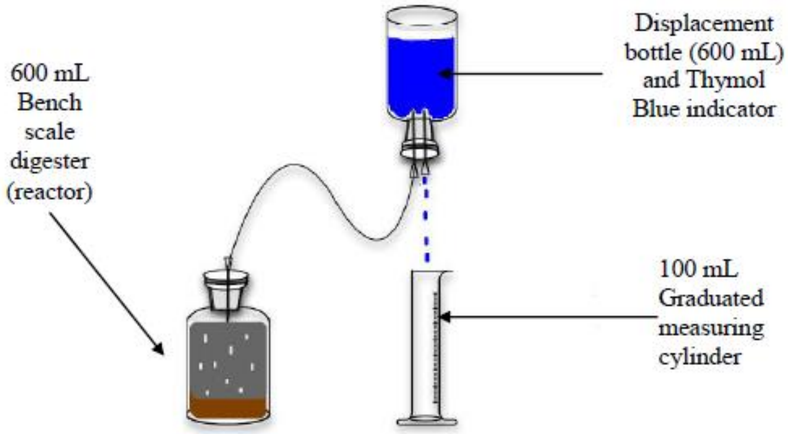


Figure 4-3: Schematic diagram depicting the setup of the biochemical methane potential tests (Tawona, 2015)

4.2.4 Analytical methods

The total solids (TS) and volatile solids (VS) in the feedstocks and inoculum were analysed using standard techniques at the beginning of the AD process and at the end of the 40 d incubation period (Labatut et al., 2011). TS content was determined after drying the sample in an oven overnight at 105 °C. VS content was calculated as TS minus the ash content after ignition at 550 °C in a muffle furnace. The pH levels of the feedstock solutions were measured with a calibrated pH metre (Model 410A, Labotec Orion, South Africa). Daily methane gas production was measured directly as the volume of liquid collected in the measuring cylinders.

4.2.5 Data analysis

The results of all the volume measurements were reported at standard temperature and pressure (STP) (273.15 K,). Daily temperature (T_m) and atmospheric pressure (Antoniou et al.) were recorded with every measurement of methane volume (V_S). These values were used to calculate the gas volumes at standard conditions (V_{STP}) according to Equation 4-1 below.

$$V_{STP} = V_s x \frac{T_{STP}}{T_m} x \frac{P_m}{P_{STP}} \quad (4\text{-}1)$$

T_{STP} and P_{STP} represent standard temperature (0 °C) and standard pressure (760 mm Hg), respectively. Daily methane volume was recorded in mL, whereas cumulative methane yield was calculated and standardized to mL CH_4/g VS.

4.2.6 Mathematical models to determine theoretical methane production

Theoretical methane production potential from substrate elemental composition

The feedstock used was characterized to obtain its elemental composition (Table 4-4). The elemental composition can be used, according to Franco et al. (2007), to estimate the maximum theoretical biogas and methane yield. Buswell's equation can be used to calculate the theoretical methane yield (Buswell and Neave, 1930).

$$\mathrm{C_aH_bO_cN_d} + \left(\mathrm{a} - \frac{\mathrm{b}}{4} - \frac{\mathrm{c}}{2} + \frac{3\mathrm{d}}{4}\right)\mathrm{H_2O} \rightarrow \left(\frac{4\mathrm{a}+\mathrm{b}-2\mathrm{c}-3\mathrm{d}}{8}\right)\mathrm{CH_4} + \left(\frac{4\mathrm{a}-\mathrm{b}+2\mathrm{c}+3\mathrm{d}}{8}\right)\mathrm{CO_2} + \mathrm{dNH_3} \quad (4\text{-}2)$$

Equation 4-2 above describes the complete degradation of all the carbon in the substrate. The maximum theoretical biogas production (B_{th}) and the theoretical methane production (M_{th}) can be estimated from Equations 4-3 and 4-4 respectively.

$$B_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{a22.415}{12a+b+16c+14d} \quad (4\text{-}3)$$

$$M_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{\left(\frac{4a+b-2c-3d}{8}\right)22.415}{12a+b+16c+14d} \quad (4\text{-}4)$$

The Buswell equation (Roati et al., 2012) can be used to select promising substrates for further examination in the laboratory and in a pilot scale test.

4.3 RESULTS AND DISCUSSION

4.3.1 Characterization of substrates

Characterization tests were conducted on the substrates and inoculum as presented in Table 4-2. The substrates were tested for all the compositions shown in Table 4-2 below.

Table 4-2: Characteristics of feedstocks and inoculum

Composition (%)	Substrate		Inoculum (cattle dung)
	Cassava Peel (CP)	Cattle Manure (CM)	
Moisture Content	79.68 ± 0.01	69.08 ± 0.15	75.20 ± 0.34
Total solids	20.32 ± 0.12	30.92 ± 0.12	24.80 ± 0.95
Volatile solids	75.51 ± 1.01	94.64 ± 4.21	84.67 ± 0.57
Starch	61.42 ± 0.21	ND	ND
Sugar	77,34 ± 0.11	ND	ND
Total nitrogen	0.87 ± 0.14	1.14 ± 0.05	2.06 ± 1.15
Total carbon	51.91 ± 0.01	53.95 ± 0.25	35.92 ± 0.17
Ash	4.98 ± 0.31	1.66 ± 0.44	3.80 ± 0.17
Phosphorus	0.20 ± 1.21	0.12 ± 0.73	0.42 ± 0.03

ND = Not determined

The CP has high starch content (approximately 61.42%) and is rich in carbohydrates. It has a sugar content of approximately 77%. It also contains approximately 79.68% moisture, 4.98% ash, and 0.2% phosphorus. On the other hand, CM has a moisture content of 69.08%. The C/N ratio of the CP was 45:1, which is considered very high compared to the optimum ratio range of 20–30:1 for maximum biogas yield (Okudoh et al., 2014).

4.3.2 pH of substrate solution

At the start of the experiment, the pH values of substrate solutions in the BMP batch reactors were measured and recorded. Table 4-3 presents the average results for all the runs.

The pH of the feedstock is an important parameter in determining the efficiency of an anaerobic digester (Kondusamy and Kalamdhad, 2014). The pH level can drop below 5 during the production of organic acids, which occurs during acetogenesis (Arsova, 2011). According to Liu et al. (2008), the optimal pH range for obtaining the highest biogas yield by AD is 6.5–7.5. Table 4-3 shows that the pH of the substrates is within this optimal range. The initial pH of all the substrates ranged from 6.51–7.41 and was within a favourable range. However, during the fermentation process, the pH was monitored and measured every five days. To neutralize pH within the bottle reactor, $NaHCO_3$ (10 g/L) was added when necessary (Ai et al., 2014).

4.3.3 Methane production

Daily methane yield at different ratios

The methane production rates under mesophilic conditions for the different mono- and co-digestion ratios, which are based on the average results for daily methane production from the three runs conducted, are presented in Figure 4-4. From Day 1, all substrates began to produce methane. However, the mixture with the CM:CP ratio of 20:80 produced the highest methane yield of 62.69 mL, followed by the ratio 80:20, with 55.57 mL, 100:0 with 51.19 mL, and 0:100 with 28.80 mL. The high yield of biogas on Day 1 could be attributed to the acclimation of the inoculum (Steinmetz et al., 2016).

An interesting decrease in the biogas yield, which could have been the result of an abatement in methane production caused by acidification in the batch reactors (Kong et al., 2016), was observed after Day 1. The pH was measured at this stage to confirm the acidification in all batch reactors, and the average results are presented in Table 4-3. According to Ali Shah et al. (2014), acidification is expected to occur within the first few days of AD unless a pH control mechanism is instituted.

Table 4-3: Average pH on Day 2 of the biochemical methane potential tests

Substrate	Average pH on Day 0	Average pH on Day 2
Cassava (100:0)	7.07 ± 0.08	6.02 ± 0.09
Cattle manure (0:100)	6.62 ± 0.14	5.71 ± 0.14
Inoculum (cattle dung)	6.86 ± 0.34	-
CM:CP (80:20)	6.54 ± 0.03	5.50 ± 0.11
CM:CP (20:80)	7.30 ± 0.14	5.85 ± 0.26

After Day 7, all reactors began to yield less methane. It was suspected that this abatement in methane production was caused by acidification in the batch reactors. The co-digestion CM:CP mixture of ratio 20:80 exhausted its methane yield after 38 d, while the other BMP mixtures (CM:CP 100:0, 0:100, and 80:20) did so after 39 d (Figure 4-4). The maximum methane yield, 91.05 mL, was produced on Day 6 by the CM:CP co-digestion mixture with the ratio 20:80, which otherwise had an average yield of 20.97 mL/day. The other BMP mixtures, that is, with CM:CP ratios of 100:0, 0:100, and 80:20, produced maximum methane yields of 61.42 mL, 38.15, and 52.28 mL respectively. The experiments were terminated at 40 d, when methane production stopped.

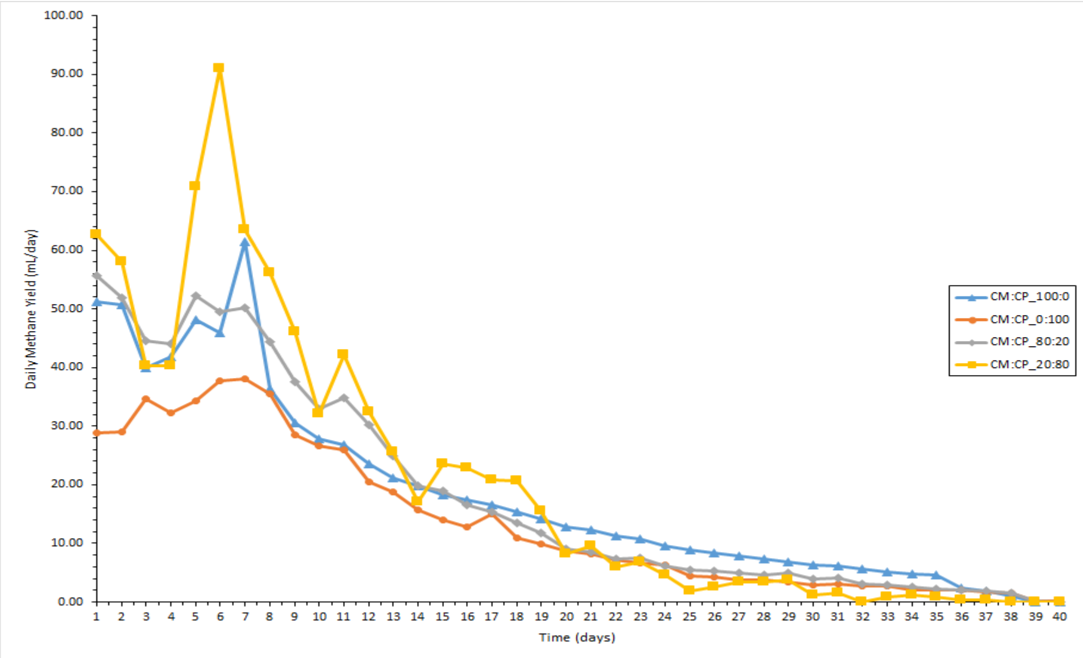


Figure 4-4: Daily methane gas, over 40 d, from different ratios of cattle manure to cassava peel

Cumulative methane yield at different ratios

The cumulative methane yield of the substrates tended to follow the horizontal asymptote representing the maximum methane production per gramme of VS (CH_4/g VS) achievable from each substrate (Esposito et al., 2012). In Figure 4-5, the x-axis displays the observation time in days, whereas the corresponding cumulative methane yield, expressed as mL CH_4/g VS, is displayed on the y-axis. Mono-digestion at the CM:CP ratio of 0:100 was inhibited, and it had a low cumulative methane yield of 61.75

mL/g VS (Figure 5). The highest cumulative methane yield was obtained from co-digestion of CM:CP at a ratio of 20:80 (96.40 mL/g VS), which was higher than that of the other co-digestion processes. The highest cumulative methane yield resulted from the mixing ratio in which the CM provided the nutrients, appropriate C/N ratio, and sufficient microorganisms required for AD (Kennedy et al., 2015). The final cumulative methane yields from the co-digestion of CM:CP of ratios 80:20 and 20:80 were 739.97 mL and 838.70 mL respectively, with average cumulative methane yields of 652.2 mL/day and 431.0 mL/day, respectively. The order of methane yield is 20:80 > 100:0 > 80:20 > 0:100, which could be attributed to the good digestibility of the CM and better interactions between the different substrates and the CM.

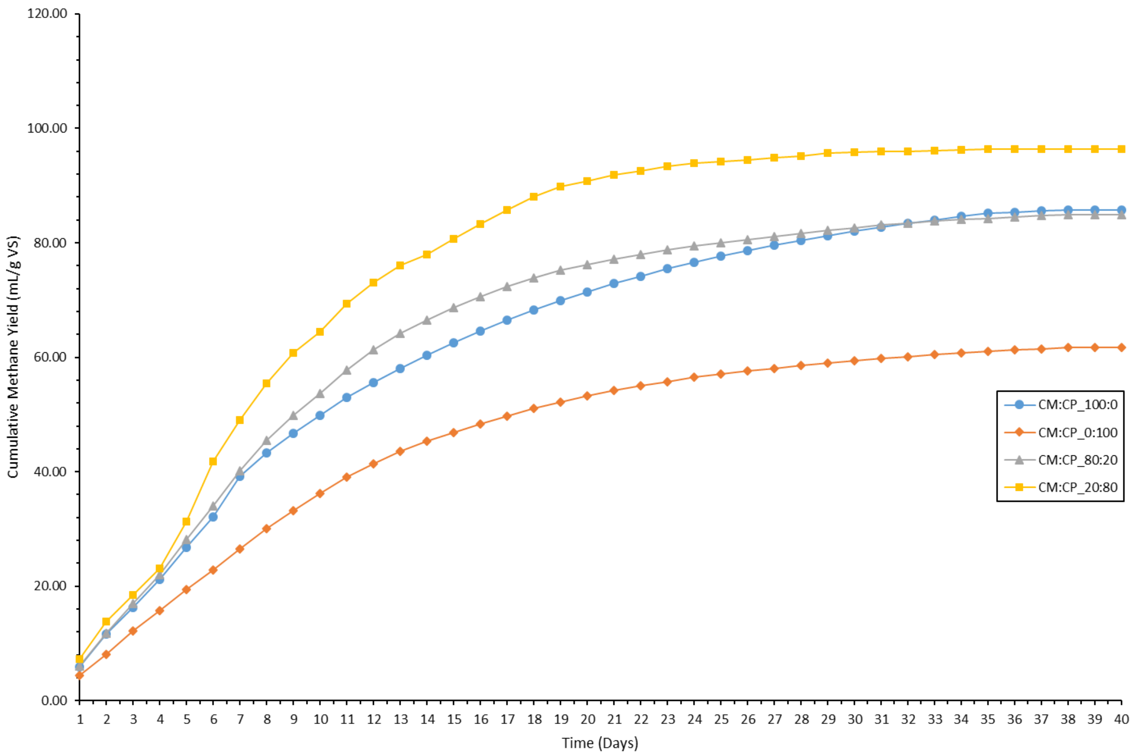


Figure 4-5: Cumulative methane gas over 40 d from different ratios of cattle manure to cassava peel

According to Esposito et al. (2012), the cumulative methane yield curve can be divided into three main phases: initial, intermediate, and final (Figure 4-5). The initial phase was characterized by a steady increase in the cumulative methane yield. According to (Mata-Alvarez, 2002), the daily methane yield affects the shape of the cumulative methane yield. This implies that, if the daily methane production rates are high in the first few days, it will result in a more pronounced reverse L-shaped curve. The intermediate phase was characterized by a higher bio-methanation rate than the initial phase. This is shown by an increase in the slopes of the cumulative methane production curves after Day 5, which is a result of the pH correction.

Determining the effect of co-digestion on ultimate methane yield using mathematical models

The biogas yield was mathematically predicted using the elemental composition of the substrates. These were compared with experimental results. The mathematical model used was described in Equations 4-3 and 4-4, which were derived from Buswell’s equation and used to estimate ultimate methane yield from the different CM:CP co-digestion ratios. The mathematical estimates of biogas yield obtained are presented in Table 4-4.

Table 4-4: Mathematical ultimate methane yield of different co-digestion mixtures using elemental analysis

Sample	Elemental analysis					C, H, O, N coefficients				Molecular formula	$B_{th}\left[\frac{m^3}{kg_{vs}}\right]$	$M_{th}\left[\frac{m^3}{kg_{vs}}\right]$
	pH	N	C	H	O	a	b	c	d			
CP	7.07	0.87	51.91	5.90	41.79	69.61	94.94	42.03	1	$C_{70}H_{95}O_{42}N$	0.97	0.50
CM	6.62	1.14	53.95	6.39	36.82	55.21	78.47	28.26	1	$C_{55}H_{79}O_{28}N$	1.03	0.56
CM:CP (80:20)	6.54	1.10	54.24	6.37	38.28	57.48	81.60	30.43	1	$C_{58}H_{82}O_{30}N$	1.01	0.54
CM:CP (20:80)	7.30	0.92	52.31	6.00	40.77	66.00	90.81	38.58	1	$C_{66}H_{91}O_{39}N$	0.98	0.51

The results presented in Table 4-4 show an interesting trend. The ultimate methane yield obtained from mono-digestion with CM, followed by co-digestion of CM:CP at a ratio of 80:20, were 0.56 m^3/kg VS and 0.54 m^3/kg VS respectively. The lowest methane yield was obtained from mono-digestion with CP (0.50 m^3/kg VS). These results support the outcome obtained by Shah et al. (2015) that co-digestion improves the methane yield if the correct ratios are used.

4.4 CONCLUSION

Co-digestion remains a suitable and simple method to improve the biogas production efficiency of mono-feedstock substrate. At similar ratios, the co-digestion of feedstock substrate at different ratios is more suitable for maximum biogas production. Co-digestion helps to balance the nutrient ratio essential for microorganisms. The chemical composition of cassava showed a high biogas production potential due to high carbohydrate, dry matter (TS), and VS content, and low fibre content.

The highest methane production was achieved from the CM:CP co-digestion ratio of 20:80, whereas the mono-digestion of CP resulted in the lowest daily and cumulative methane yields. The study showed that increasing the CM ratio in relation to CP increased the cumulative biogas yield. This result could also introduce the possibility of using energy crops such as cassava as a capping measure for landfills, which could assist in the utilization of the landfill site after closure. Cassava peel could also be used for biogas generation at harvest. The results obtained from this study could be used as a basis to design a plot-sized anaerobic digester, and in turn large-scale anaerobic digesters, thereby providing a source of renewable energy for low income communities.

CHAPTER 5:

COMPARISON AND MODELLING OF BIOGAS PRODUCTION FROM UNPEELED AND PEELED CASSAVA TUBERS AT A MESOPHILIC TEMPERATURE

Nathaniel Sawyerr[1*], Cristina Trois[2], Tilahun Workneh[3], Vincent Okudoh[4]

[1,2]Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

[3]Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

[4]Department of Biotechnology and Consumer Sciences, Cape Peninsula University of Technology, Cape Town Campus, South Africa.

PREAMBLE

Based on the identified feedstock in chapter 2 and the promising theoretical results, further investigation was conducted on the biogas yield of Peeled Cassava Tuber (PCT) and Unpeeled Cassava Tuber (UCT). Chapter 5 aims to define the effect of the cassava peels on the biogas yield by comparing the peeled cassava tuber and unpeeled cassava tuber. Additionally, the effect of inoculum on the biogas yield is also investigated.

This chapter is presented in the form of a journal article published in *International Journal of Mechanical Engineering and Technology (Scopus),* minor changes were made to improve the flow. The copy of the original published research article can be found in Appendix P4.

Received; Accepted 08 December 2018, ISSN Print: 0976-6340 and ISSN Online: 0976-6359

ABSTRACT

The production of energy from biomass such as an energy crop is gaining momentum due to the steady increase of the world population, economic growth and the accelerating cost of fossil fuels. In recent years, progressive climate change related to global warming and rampant Green House Gases emissions necessitates applied research in renewable energy generation from different sources. The purpose of this study, therefore, was to evaluate the potential of production of biogas from unpeeled and peeled cassava tubers at a mesophilic temperature of 37 ºC in a 50-litre laboratory scale biogas digester, with cow dung (inoculum) as source of methanogens. The experimental design consists of two biomass raw materials (i.e. whole cassava and peeled whole cassava tuber). The highest biogas yield of 635.23 L/kg VS was obtained from peeled cassava tuber anaerobic fermentation using inoculum followed by the digestion of peeled cassava tuber as raw material without inoculum which led to the production of 493.35 L/kg VS. The feedstock of peeled cassava with inoculum, produced 28.75% more gas yield when compared to peeled cassava without inoculum. The Modified Gompertz model fitted the cumulative experimental methane gas data well. The Gompertz Model with the newly developed coefficients was used to predict the maximum biogas yield at day 40. The validated results show that peeling the cassava tuber increases the biogas yield by 38% compared to the unpeeled cassava tuber.

KEYWORDS: Biomass, Anaerobic Digestion, Biogas, Peeled Cassava Tuber, Kinetic Model, Unpeeled Cassava Tuber

5.1 INTRODUCTION

Supply and consumption of energy are important factors in improving living standards in off-grid communities (Twidell and Weir, 2015). Evidence shows that global demand for energy is increasing with the steady growth of the world population, economic growth and increased energy usage (Hagos et al., 2017, Sorrell, 2015). Reliance on fossil fuels has also increased over the years and will soon result in the depletion of fossil fuel resources. It is crucial that we explore alternative energy sources that are sustainable and renewable for future generations (Panwar et al., 2011). Considering the need for sustainability in resource and environmental management, research focused on harnessing energy from sustainable sources is on the increase. These sustainable sources are majorly renewable in nature. Some of these renewable sources include small hydro, wind, geothermal, solar, and biomass. Of all these sources, the biomass is distinct and different from other sources of renewable energy. This is majorly due to its special feature as regards use, control, collection of organic wastes and concurrent production of fertilizer and water for agricultural use (Memon et al., 2012). Furthermore, biomass has no geographical limitation and can be processed to biogas using local technologies. Biogas is a gas generated when organic matters are broken down in the absence of oxygen (anaerobic digestion). According to Gelegenis et al. (2007), “organic waste such as dead plant and animal material, animal faeces, and kitchen waste can be converted into a gaseous fuel called biogas.” This means that biogas can be produced for energy even in remote communities without enough wind speed and solar irradiation for wind turbine technologies and solar technologies respectively. This will help in increasing electrification rates worldwide.

The renewable energy generation during anaerobic digestion of biomass has mainly been used for the degradation of biomass or any waste materials or toxic compounds (Khalid et al., 2011). However, recently, there has been increased interest in the production of biogas from carbohydrate rich energy crops by means of anaerobic digestion (Choi and Lee, 2015). Based on this, the local production of energy from carbohydrate rich energy crops is essential for the minimisation of emissions and increase of electrification rates in Africa. For instance, South Africa, as one of the countries with the highest inequality in the world (Gini coefficient = 0.7), could benefit from the adoption of anaerobic digestion technology for energy crops (Bhorat, 2015), thereby assisting local communities in gaining access to electricity like their urban communities. To achieve this, a laboratory-scale research on the ultimate biogas and methane yield from new energy crops such as cassava is of importance. Much research attention has been given to biogas production from industrial wastewaters in South Africa while there is a huge interest in industrial waste water treatment for use of the treated water for other purposes (Stafford et al., 2013). However, little research attention has been dedicated to energy production from energy crops.

Some recent studies have focused on using raw materials such as municipal waste, agricultural waste, sewage, manure, plant material, food or green waste in developing novel methods of biogas production. Klimiuk et al. (2010) carried out an investigation on the ability of silage obtained from crop species namely*: Zea mays L., Sorghum saccharatum, Miscanthus giganteus and Miscanthus sacchariflorus*, to produce methane. It was observed that due to the higher crude content in *Miscanthus spp.,* the volumetric methane obtained from *Zea mays L. or S. saccharatum silages* were higher than those from the *Miscanthus giganteus or sacchariflorus* silages at a hydraulic retention time of 60 days. The methane productivity of *Miscanthus sacchariflorus* was however higher than that of *Miscanthus giganteus* at comparable feedstock lignin concentrations. The efficiency of cellulose conversion was observed to be highest in *Zea mays L.* (88.9%,), followed by *Sorghum saccharatum* (83.6%), *Miscanthus giganteus* (59.7%) and *Miscanthus sacchariflorus* (52.1%).

Maragkaki et al. (2018) carried out an experimental investigation on the effect of using a mixture of small amount of agro-industrial by-products, co-digesting sewage sludge and food wastes for biogas production. The experiment was carried out using lab-scale reactors under mesophilic conditions at a hydraulic retention time of 24 days. Jiang et al. (2018) carried out an investigation to validate the production of bio-hythane using a two-stage fermentation process of cassava with recirculation and with repeated batch experiments. The effect of hydraulic retention time was clarified and the effects of nickel, nitrogen, sulfur and cobalt supplements used in the fermentation process, were investigated. It was observed that the increase in hydrogen, hydrolysis and acidogen producing bacteria was ensured by sufficient presence of nickel, nitrogen, sulfur and cobalt supplements in the fermentation process, with the recovery of a sustainable hythane fermentation metabolism.

Castrillón et al. (2011) carried out an evaluation on the production of biogas through the co-digestion of cattle manure with crude glycerin extracted from biodiesel after the cattle manure was pre-treated using the sonication technology of ultrasound. It was observed that under moderate temperatures, the addition of a light amount of glycerin increased biogas production by 400% while sonication of cattle manure mixed with glycerin increased biogas production by 800%. Furthermore, an experimental study has also been carried out by Zema et al. (2018) to obtain biogas from olive mill wastewater (OMW) blended with other agro-industrial by-products.

Gilson (2017) performed a cost-benefit analysis on the use of wetland plants as a supplement for biogas production, thereby conducting an investigation on how harvest time affects the biogas production of wetland species such as *Phragmites australis* and *Glyceria maxima.* It was observed that the midyear harvest time produced the highest generated revenue. Although using wetland plants solely for biogas production is not currently profitable, Gilson concluded that placing higher premium on the value of socioeconomic benefits such as global warming mitigation and increased biodiversity will make it economically attractive in future. Ebrahimi-Nik et al. (2018) carried out a study on the benefits of using drinking water treatment sludge as a supplement for biogas production from food waste. It was observed that the treatment sludge enhanced the products of biogas and lessened the time of retention and lag phase.

A preliminary desktop review undertaken prior to this study reveals that the energy generating potential of some plants are yet to be explored. These include locally grown plants species in sub-Saharan Africa. Energy crops such as fodder beets and cassava have been identified as major crops for biogas production since they are drought-tolerant and can, thus, give good yield in South Africa as well as elsewhere in the region. This article explores the potential of cassava as an energy crop, as there is a paucity of research on cassava biomass (Okudoh et al., 2014).

Cassava is cultivated in many African, American and Asian countries. It is a starchy root crop with starch concentration ranging from 20–35% and 80% to 86% when fresh and dried respectively (Uchechukwu-Agua et al., 2015). In most West-African counties, cassava is the second most important staple food, but it is still a minor food plant in South Africa. For this reason, the conflict between food security and energy is inconsequential (Arc.Cassava, 2014). Due to its high carbohydrate concentration of 4.742 kg/carb per hectare (Nuwamanya et al., 2012), cassava chemical composition has great potential for the production of bioenergy, especially biogas (Okudoh et al., 2014). Cassava has several advantages compared to other energy crops as it has the ability to grow in areas with low fertility and has the highest yield of carbohydrates compared to sugarcane and sugar beet (Okudoh et al., 2014). Therefore, the main objective of this research is to evaluate the production of biogas from unpeeled cassava tubers (UCT) compared with peeled cassava tubers (PCT) at a mesophilic temperature ($37°C$) in the absence and presence of inoculum. This study is a pilot study on the production of biogas from cassava in South Africa. It is expected that this study will contribute towards establishing an accurate technique for biogas quantification using UCT and PCT, and contribute to knowledge on the suitable feedstock that can provide an optimum biogas yield.

5.2 MATERIAL AND METHODS

This section presents the methodological approach adopted in this study. The research involved (1) collecting data on the mono-digestion of unpeeled cassava tubers (UCT^0) and peeled cassava tubers (PCT^0) without inoculums; (2) comparing data on the biogas yield from mono-digestion for UCT and PCT; (3) investigating the effectiveness of inoculums for biogas production from unpeeled cassava tuber with inoculums (UCT^1) and peeled cassava tuber with inoculums (PCT^1); and (4) investigating the daily production rate of both peeled and unpeeled cassava in the presence and absence of inoculum.

5.2.1 Collection and Pre-treatment of Substrates and Inoculums

Fresh cassava tubers (200 kg) were collected from a cassava plantation in the Nampula Province of Mozambique. A hundred kilogrammes of the collected fresh cassava tubers were mechanically pre-treated by peeling, while the remaining 100 kg was not peeled. Both the peeled and unpeeled cassava was washed with tap water and chopped into pieces of about 1 cm^3 using a sharp knife. Thereafter, it was dried in sunlight for two days (Figure 5-1). All prepared feedstock were stored in a refrigerator at 4 ˚C until use in the experiment. The dried cassava tubers were milled with a scientific Republic of South Africa hammer mill that is equipped with a 2 mm sieve mesh to obtain cassava flour. The properties of the substrates are shown in Table 1.

The inoculum used for this study was fresh cattle dung (FCD) (Figure 5-2) collected from the University of KwaZulu-Natal’s (UKZN) Ukulinga Research Farm in Pietermaritzburg, South Africa. It contained all the required microbes essential for the anaerobic digestion process. The inoculum was characterized for moisture content, total solids, volatile solids, total carbon, total nitrogen, pH, C/N Ratio, ash and phosphorus.

Figure 5-1: (A) sample of unprepared cassava tubers, (B) sample of peeled cassava tubers (PCT), (C) sample of cut peeled cassava tubers, (D) sample of cut unpeeled cassava tubers (UCT), and (E) Cassava Flour

5.2.2 Inoculum Preparation

The FCD was mixed with water to a ratio of 1 kg cattle dung: 2 litres water (i.e. 1:2) to form a slurry (Nasir et al., 2015). The slurry inoculum was filtered by passing it through a 0.5mm sieve diameter to separate the solid content from the slurry. The filtered FCD slurry was kept in an airtight container at 4°C. Prior to use, it was acclimated and degassed at 35°C for three weeks to minimize the production of methane from the inoculum. An inoculum: substrate ratio of 1:2 was used for the digestion (Angelidaki et al., 2009) after purging the system of oxygen with ultrapure N_2 gas to create an anaerobic environment.

Figure 5-2: Fresh cattle dung (Inoculum)

5.2.3 Experimental set up

Peeled cassava tubers (PCT) and unpeeled cassava tubers (UCT) were weighed and the biomass was mixed with tap water to a volume ratio of 1:2 (Biomass: Water). This was done to maintain total solids in the digester of between 8 and 15%, which is the acceptable range for wet anaerobic digestion (Liu et al., 2015). The slurries were mixed properly to obtain a homogenous condition. The prepared slurry was fed into the batch type digester (Figure 5-3) and digested anaerobically until no biogas was produced (zero biogas yield). The characterization of the slurry feedstock used in the anaerobic digestion is presented in Table 1. The initial pH for all the slurry was adjusted to 7.0 ± 0.1 by using NaOH solution 1 N.

5.2.4 Experimental Design

A laboratory scale experiment was conducted with a 50-litre open head drum (Figure 5-3B). A 50 mm PVC pipe was connected to the digester to feed it with the substrate. The mixing was done manually and operated by a pitched 3-blade paddle impeller (Figure 5-3B). The working volume of the bio-digester was 45 litres, which is about 90% of the volume of the digester.

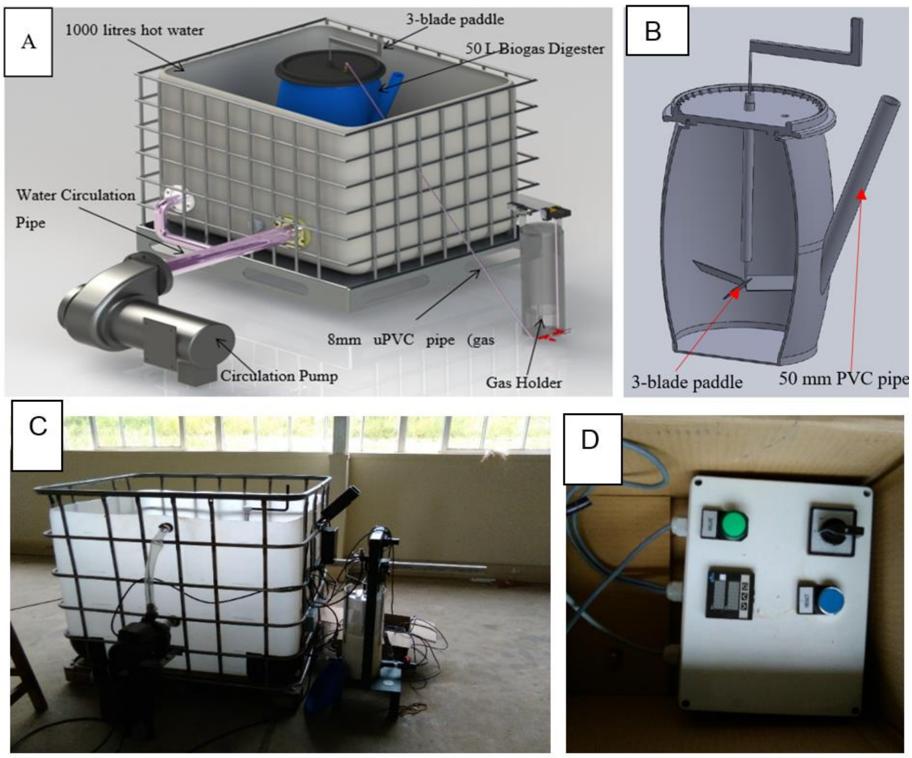


Figure 5-3: (A) Model for generation of biogas from cassava peel and peeled cassava tubers, (B) Section of digester showing the 3-blade paddle, (C) Biogas generation experimental setup, and (D) programmable logic controller (PLC)

The digester was placed in a hot-water bath that keeps it at its desired operating temperature. This hot-water bath was constructed with a 1000 *l* intermediate bulk container (IBC) (Figure 5-3A). The IBC was fitted with two temperature adjustable heating elements to control the water temperature and a recirculation pump (Figure 5-3A & Figure 5-3C), which was used to recycle the hot water through different points in the IBC to ensure even heat distribution and convective heat transfer around the digester. The temperature of the water was kept at 37 ºC as the experiment was carried out at a mesophilic temperature.

A gasholder system (GH) connected to programmable logic controller (PLC) was used to measure the biogas yield per day. After the setup of the GH, the PLC system was connected to a single phase 220V, 50Hz power outlet (Normal wall plug). The PLC was turned on by turning the power button (Figure 5-3D). When biogas is produced in the digester, the gas moves through the 8mm uPVC pipe (Figure 5-3A) into the inner cylinder of the gasholder. The gasholder is filled with water up to the top part where the aluminum isolation stops (Figure 5-4A & Figure 5-4B). Due to the pressure formed inside the inner cylinder by the gas from the digester, the cylinder moves upwards as more gas is produced. The gas cylinder will eventually come in contact with the Button limit switch and activate it. When the switch is activated, the solenoid valve will be activated. This can be seen when the valve light is lit on the PLC. When the valve is activated, the biogas becomes vented. As the biogas is vented, the gas cylinder will move down, eventually activating the lever limit switch which will deactivate the solenoid valve which is the end of one complete gas cycle.

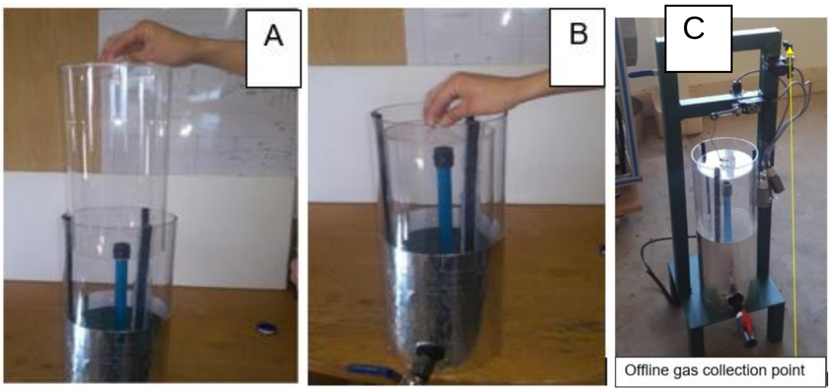


Figure 5-4: Gasholder with moving inner gas cylinder, up inner gas cylinder (A), down inner gas cylinder (B), and Gas chromatography connection point (C)

UCT and PCT were separately examined in the absence and presence of inoculum with a single digestion process to determine and compare performance. The digester was fed with 40 litres of the relevant substrate and was inoculated with a slurry of FCD. The inoculum was used to apply the bacterial concentration in the digester. After feeding, the digester with the desired amount of feedstock was flushed with nitrogen gas to create an anaerobic environment, where after the digester was closed. The mesophilic batch tests were conducted at a temperature of 37 ºC. This temperature was maintained throughout the whole experiment and was monitored using a mercury thermometer. The biogas volume produced was measured using a gasholder (Figure 5-4C) and the methane content was measured using chromatography, the biogas was collected at the collection point as indicated in Figure 5-4C. All gas volumes reported have been corrected to STP (0 ºC, 110.3 KPa) as described by Walker et al. (2009). The substrate was manually stirred using the 3-bladed paddle for about ten (10) seconds once a day before measurement of the biogas volume.

5.2.5 Biogas measurement and analytical methods

The programmable logic controller (PLC) was used to measure the biogas produced daily. The gas composition was analysed offline by means of chromatography. Total solids (TS) and total volatile solids (VS) were determined at 104^0C and 550^0C, respectively, using standard methods (Helrich, 1990, Federation and Association, 2005). Additional parameters were also determined total carbon and nitrogen contents using the CNS-2000 Elemental Analyzer (Leco Corporation, USA).

The starch concentration in the cassava tubers was determined using spectrophotometry at 580 nm absorbance in the soluble form and the presence of iodine (Gales, 1990). The experiment ran until zero biogas was reached.

5.2.6 Modelling of production during biogas digestion

The cone model (Zhen et al., 2015), and modified Gompertz model (Syaichurrozi and Sumardiono, 2013) were used to model the experimental biogas yield. The model parameters such as y_m, λ, U, k_{hyd}, n, k were optimised using non-linear regression analysis with the help of Polymath 6.10 software. The equations of the cone model (5-1), the modified Gompertz model (5-2) are presented below:

$$y(t) = \frac{y_m}{1 + (k_{hyd}.t)^{-n}}, t > 0 \tag{5-1}$$

$$y(t) = y_m. \exp\left\{- \exp\left[\frac{U.e}{y_m}(\lambda - t) + 1\right]\right\}, t \geq 0 \tag{5-2}$$

where:

y_m = biogas yield potential (Lkg^{-1} VS),

y(t) = cumulative biogas at digestion time t days (Lkg^{-1} VS),

U = the maximum biogas production rate (Lkg^{-1} VS. day),

λ = lag phase period or minimum time to produce biogas (days),

t = cumulative time for biogas production (days),

e = mathematical constant (2.718282),

k_{hyd} = hydrolysis rate constant (day^{-1}),

n = shape factor, and

k = the biogas rate constant (day^{-1}).

5.2.7 Data analysis

The data were analyzed using ANOVA for variance and coefficient(s) of determination (r^2) by sigma (λ) (2-tailed). The least significant was used to investigate the statistical significance of the presence of inoculum in the feedstock. All the data were analyzed using the Statistical Package for the Social Sciences (SPSS) model, version 24 of 2016.

5.3 RESULTS AND DISCUSSION

5.3.1 Characterization of substrates

The physico-chemical properties of UCT, PCT and the inoculum are shown in Table 5-1. The results show that there was no significant difference ($P \leq 0.05$) between the peeled and unpeeled cassava tubers in terms of biogas yield. The UCT had maintained higher moisture content (76.56%) compared to the moisture content in PCT (61.58%). These results are favourable as they are within the optimum moisture content range of 60–95% (Demetriades, 2008) for the digester to perform efficiently. Moisture content of less than 20% will result in no biogas generation (Rilling, 2005).

The pH value of the feedstock used in the anaerobic digester is critical for optimum biogas yield (Sichilalu et al., 2017). The pH of UCT, PCT and inoculum (CD) is 6.90, 6.87 and 7.30, respectively. These levels are within the acceptable pH range of 6.0–8.0 (Hettiaratchi et al., 2015). The optimal pH level during the fermentation process within the digester is between 5 and 6, while the optimal pH during the methanogenesis is between 6.8 and 7.5 (Hettiaratchi et al., 2015).

Table 5-1 shows that the total solids of both UCT and PCT (38–43 %) were out of the recommended range (7% to 10%) for best biogas production (Kigozi et al., 2014). The recommended range seeks to avoid solids settling down in the lower part of digester.

The fresh cattle dung inoculum was in the correct range. Peeling the cassava tubers did affect the C/N ratio, but the effect was not significant at P≤0.05 level of significance.

Table 5-1: Characterizations of substrates used in the experiments

Parameter	Substrate		FCD ±SD	Significance level (P-Value)
	UCT ±SD	PCT ±SD		
Moisture Content (%)	76.56 ± 3.12	61.58 ± 2.11	80.34 ± 0.12	0.006*
Total Solids (%)	38.43 ± 1.01	42.25 ± 1.51	11.95 ± 0.10	0.083
Volatile Solids (%TS)	94.21 ± 0.32	91.27 ± 0.52	61.57 ± 0.01	0.016*
pH	6.9 ± 0.91	6.87 ± 0.47	7.30 ± 0.11	<0.001*
Starch (%)	78.38 ± 1.34	76.32 ± 2.01	ND	0.184
Total Nitrogen (%)	0.51 ± 0.22	0.53 ± 0.44	2.15 ± 0.41	0.189
Total Carbon (%)	39.04 ± 2.31	39.67 ± 1.78	35.17 ± 1.01	0.001*
C/N Ratio	76.55 ± 10.5	74.85 ± 4.05	16.36 ± 2.46	0.106
Ash (%)	3.84 ± 0.44	3.06 ± 0.66	33.17 ± 1.10	0.310
Phosphorus (%)	0.09 ± 0.68	0.16 ± 0.57	0.03 ± 0.31	0.131

ND - Not determined; *significant at P≤0.05 or P≤0.001 level of significance.
UCT – Unpeeled Cassava Tubers; PCT - Peeled Cassava Tubers; FCD – Inoculum Fresh Cattle Dung
C/N - Carbon to Nitrogen

5.3.2 Daily Biogas Yield of Peeled Cassava Tuber with and without Inoculum

Figure 5 displays the average daily biogas yield of PCT and UCT with and without inoculum at mesophilic temperature (37 ^{o}C) over 40 days of digestion in Lkg^{-1} VS of biogas. Feedstock with inoculum started yielding biogas at a rapid rate compared to the PCT sample with no inoculum. This could be attributed to the presence of microbes in the inoculum that act readily on the substrates (Steinmetz et al., 2016).

As shown in Figure 5-5, the biogas production, as a result of the digestion of PCT, started at a rapid rate and continued to rise until it reached a peak of 32.92 Lkg^{-1} VS. It thereafter decreased between days 14 and 17. These small methane variation were as a result of variations in pH and temperature (Baltrenas and Kvasauskas, 2008, Misevičius and Baltrėnas, 2011), after which the biogas peaked at 38.04 Lkg^{-1}VS.

The feedstock comprising peeled cassava tubers with inoculum (PCT^{1}) produced the highest biogas yield of 38.04 Lkg^{-1}VS on day 19 compared to peeled cassava tubers without inoculum (PCT^0), which had its peak biogas yield at 31.81 $Lkg^{-1}VS$ on day 21. These results when compared with studies conducted by Rodriguez-Chiang and Dahl (2014) and Liu et al. (2017) show that the addition of inoculum to feedstock enhances the daily biogas yield.

The daily biogas yield for PCT without inoculum produced a flatter increasing slope of +1.696 Lkg^{-1} VS between days 1 and 21 compared to PCT with inoculum, which produced a steep slope of +1.799 Lkg^{-1} VS between days 1 and 19. The decrease in the slope of the daily biogas yield of PCT without inoculum was steep (-2.814 Lkg^{-1} VS), which signifies that the feedstock without inoculum reduced the biogas yield after a retention period of 21 days, compared to the feedstock with inoculum which reduced the biogas yield after a retention period of 19 days.

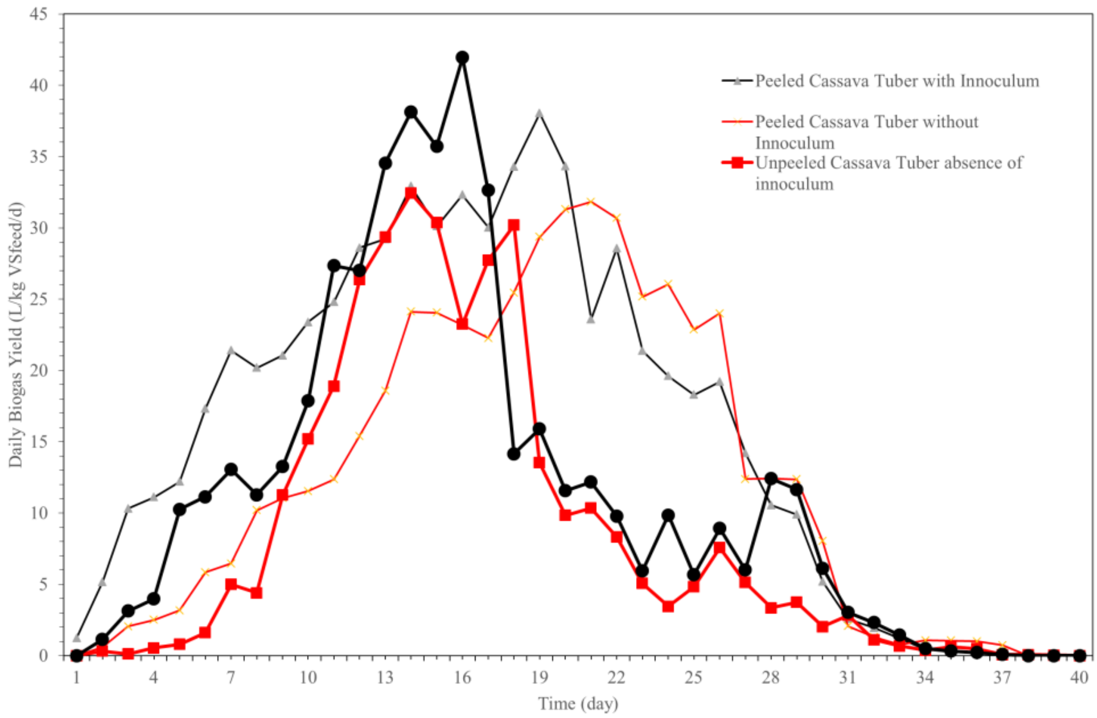


Figure 5-5: Daily biogas yield, over 40 d, from peeled cassava tuber (PCT) and unpeeled cassava tuber (UCT) with and without inoculum. Each data point is the average of the measurements of three digesters.

5.3.3 Daily Biogas Yield of Unpeeled Cassava Tubers with and without Inoculum

Figure 5-5 presents the average daily biogas production rates ($Lkg^{-1}VS$) for unpeeled cassava tubers (UCT) with and without inoculum. The UCT with FCD inoculum begin to yield biogas from the second day of digestion compared to the UCT without inoculum, which only produced a significant biogas yield on the sixth day. The maximum values of biogas production rate were 41.95 L/kg VS and 32.41 $Lkg^{-1}VS$ for UCT with inoculum and UCT without inoculum respectively. The fact that the UCT with inoculum had a higher biogas production rate may be attributed to the presence of easily biodegradable materials in the inoculum compared to the UCT without inoculum.

The production of biogas in UCT without inoculum started at a flatter rate of 0.1796 $Lkg^{-1}VS$ until day five, after which it produced biogas at a faster rate (between days 5 and 13). In comparison, the UCT with inoculum produced biogas at a faster rate from day one, and this suggests the presence of microbes in the cow dung inoculum that was added to the UCT substrate (Gebrekidan et al., 2014). The decrease in the slope of the daily biogas yield of UCT with inoculum was steep (-2.814 $Lkg^{-1}VS$) compared to that of UCT without inoculum, which signifies that the feedstock without inoculum reduced the biogas yield after a retention period of 21 days compared to the feedstock with inoculum, which reduced the biogas yield after a retention period of 19 days. The start and reduction rate of biogas is shown in Figure 5.

5.3.4 Cumulative Biogas Yield of Peeled Cassava Tubers with and without Inoculum

Figure 5-6 shows the cumulative biogas productions of peeled cassava tubers with and without inoculum. PCT with inoculum yielded a higher volume than PCT without inoculum. The total biogas produced from PCT with inoculum was 635.23 $Lkg^{-1}VS$, while that produced from PCT without inoculum was 493.35 $Lkg^{-1}VS$, which is 77% less than that of the substrate seeded with inoculum.

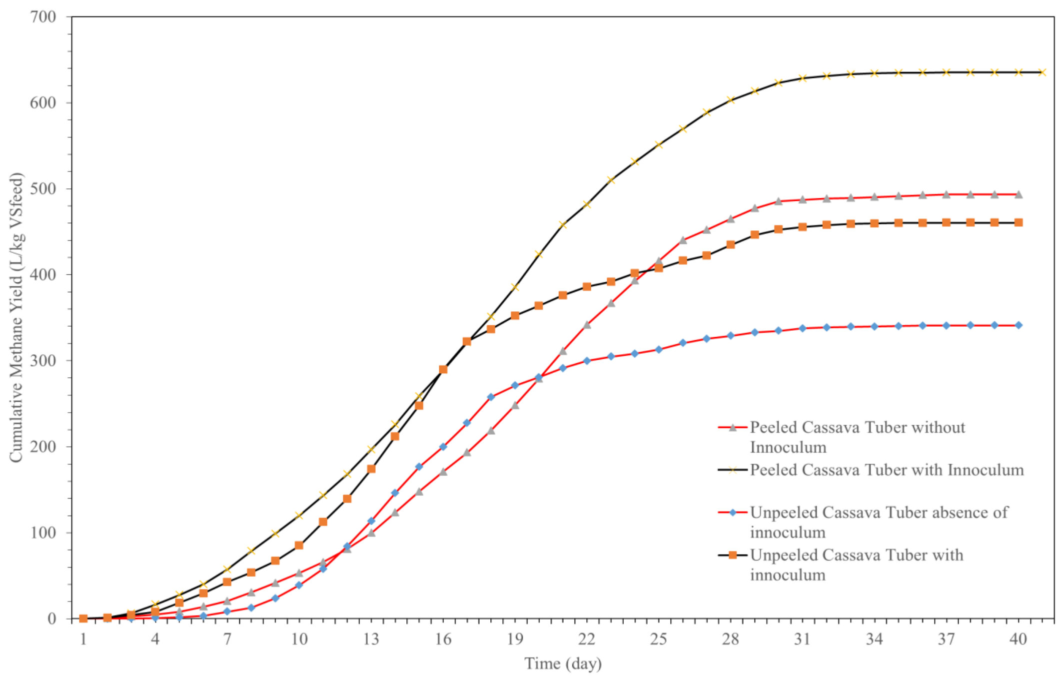


Figure 5-6: Cumulative biogas production from peeled cassava tuber and unpeeled cassava tuber with and without inoculum. Each data point is the average of the measurements of three digesters.

5.3.5 Cumulative Biogas Yield of Unpeeled Cassava Tubers with and without Inoculum

The cumulative biogas yields of unpeeled cassava tuber in the presence and absence of inoculum are shown in Figure 5-6. The unpeeled cassava tubers (UCT) with inoculum had a higher biogas yield than, UCT without inoculum. The retention period was 40 days. The biogas yield for UCT with and without inoculum was calculated to be 460.41 $Lkg^{-1}VS$ and 341.12 $Lkg^{-1}VS$ respectively. From Figure 5-6, we observe that after 15 days of digestion, approximately 51% of the final biogas yield could be obtained (Table 5-2).

5.3.6 Modelling Biogas Yield

The model parameters such as y_m, λ, U, n, k_{hyd}, k were obtained by fitting the equations to the experimental biogas yield data. Table 5-2 displays the summary of the results of both experimental and predicted biogas yield using the coefficients at day 40. Figure 5-7 presents the experimental and the calculated data using the developed model (based on the cone model), and modified Gompertz (equations 1 and 2). These models can be used to estimate the changes in gases and ultimate yield of a given substrate under specified conditions.

Table 5-2: The coefficients of determination and constants developed by fitting cone, and modified Gompertz to experimental PCT, UCT data.

MODELS	Substrate			
	PCT^0	PCT^1	UCT^0	UCT^1
CONE MODEL				
k_{hyd} (day^{-1})	0.05	0.06	0.07	0.07
N	4.15	2.99	5.10	3.76
r^2	0.99	0.99	1.00	1.00
y_m ($Lkg^{-1}VS$)	536.40	708.38	343.09	474.99
Predicted biogas yield ($Lkg^{-1}VS$) - 40 d	512.99	662.86	340.85	464.21
Measured biogas yield ($Lkg^{-1}VS$) - 40 d	493.35	635.23	341.12	460.41
Difference between measured and predicted biogas yield (%)	3.98	4.35	0.08	0.83
MODIFIED GOMPERTZ MODEL				
λ (days)	16.45	13.30	13.27	12.53
µ ($Lkg^{-1}VS.day$)	0.15	0.14	0.24	0.18
r^2	0.99	0.99	0.99	0.99
y_m (L/kg VS)	527.00	673.90	340.70	464.70
Predicted biogas yield ($Lkg^{-1}VS$) - 40 d	513.29	658.17	340.14	461.80
Measured biogas yield ($Lkg^{-1}VS$) - 40 d	493.35	635.23	341.12	460.41
Difference between measured and predicted biogas yield (%)	4.04	3.61	0.29	0.30

PCT^0: Peeled cassava tubers without inoculum; PCT^1: Peeled cassava tubers with inoculum; UCT^0: Unpeeled cassava tubers without inoculum; UCT^1: Unpeeled cassava tubers with inoculum; R^2: correlation coefficient.

Cone model

The parameters obtained as the result of fitting this model to the experimental biogas yield data are presented in Table 5-2. The coefficient(s) of determination (r^2) between the cone model and the experimental results of all the substrates are presented in Table 5-2. The r^2 values range from 0.99 to 1.00, with the unpeeled cassava tubers with and without inoculum producing the best fit. The maximum biogas cumulative yield (y_m) from the cone model was close to the experimental yield, with the percentage difference between measured and predicted ranging from 0.83% to 3.98%. These results show that the cone model fits well to the cumulative biogas yield curve for this study. The hydrolysis rate constant (k_{hyd}) measured in days indicates the hydrolysis rate of the organic materials. The higher value of k_{hyd} indicates that the organic materials of the substrates were degraded (Syaichurrozi, 2018). The bacteria inside the digesters needed shorter time to adapt, as is evident from the lower value of λ (12.53 days), which is the lag phase period and the higher value of k_{hyd} (0.07day^{-1}).

Modified Gompertz model

With reference to Table 5-2, the substrate of peeled cassava tuber with inoculum produced more y_m with a maximum biogas yield of 673.90 Lkg^{-1}VS compared to the other substrate (PCT^0, UCT^0 and UCT^1), which yielded between 340.70 and 527.00 Lkg^{-1}VS, with UCT^0 being the lowest. The high biogas yield in the peeled cassava may be attributed to the impact of the bacteria which enhanced its degradability compared to the unpeeled tubers. The higher the biogas production rate (μ), the lower the maximum biogas yield.

According to Syaichurrozi et al. (2016), the λ value shows the time it takes during anaerobic digestion for the bacteria to adapt to the substrate before commencement of the biogas yield. If a substrate has a small λ value, this signifies that it takes more time to produce biogas than substrates with greater λ. Using this information, substrates of PCT^0 require more time to adapt, 16.45 days, whereas substrates of UCT^1 require less time, 12.53 days. This result suggests that PCT^1 produces a better biogas yield compared to the other substrates.

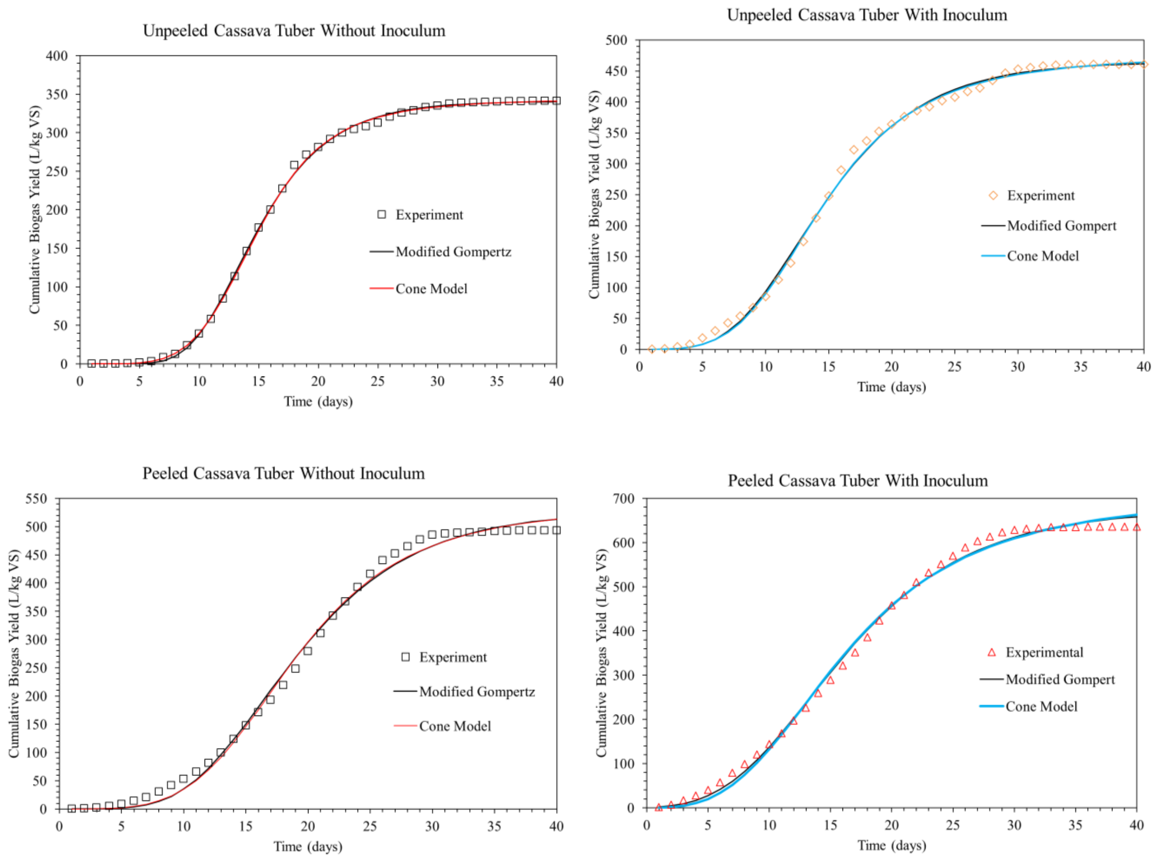


Figure 5-7: Comparison of model data and experimental data using the cone model, the modified Gompertz and the first order model

5.4 CONCLUSIONS

This study investigated the production of biogas from unpeeled cassava tuber without inoculum (UCT^0), unpeeled cassava tuber with inoculum (UCT^1), peeled cassava tuber without inoculum (PCT^0), and peeled cassava tuber with inoculum ($PCT^{1)}$ by means of batch anaerobic digestion. The data obtained in this study suggest that anaerobic digestion of PCT^1 yields the most viable results. This in turn suggests that the production of biogas from peeled cassava tuber with inoculum could be a viable alternative renewable energy source for the future. PCT^1 was more favourable in the biogas production as a result of the feedstock degradability.

The following were the main findings of the study:

- PCT^1 produced the best biogas yield, with 635.23 $Lkg^{-1}VS$ at day 40.

- The modified Gompertz model fitted well to the experimental data for the cumulative biogas yield compared to the cone model and the first order kinetic model, which was the least favourable model for predication of biogas yield.
- Peeling the cassava tubers reduces the lignin and thereby exposes the cellulose to the bacteria.

Further research is recommended on the co-digestion of PCT[1] with domestic waste or vegetable and fruit waste to increase the biogas yield additionally, efforts will focus on technology selection of small-scale biogas production and production scheduling under uncertainty of feedstock supply.

CHAPTER 6:
OPTIMIZATION OF BIOGAS YIELD THROUGH CO-DIGESTION OF CASSAVA BIOMASS, VEGETABLE AND FRUITS WASTE AT MESOPHILIC TEMPERATURES

Nathaniel Sawyerr[1*], Cristina Trois[2], Tilahun Workneh[3]

[1,2]Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

[3]Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

PREAMBLE

Based on the identified feedstock in chapter 3 and the promising theoretical results, further investigation was in chapter 6 which aimed at exploring the optimum biogas yield through co-digestion of cassava biomass, vegetable and fruits at different ratios in a single stage fed-batch anaerobic digester for biogas production. Additionally, the effect of inoculum on the biogas yield is also investigated and the results of the biogas yield were modelled using the Gompertz model.

This chapter is presented in the form of a journal article published in *International Journal of Renewable Energy Research (Scopus),* minor changes were made to improve the flow. The copy of the original accepted research article can be found in Appendix P5.

ABSTRACT

Biogas is a mixture of gases mainly methane and carbon dioxide, it is considered a clean and renewable form of alternative energy. It can be obtained through fermentation of any biomass in the absence of oxygen called anaerobic digestion. The objective of this paper is to obtain the optimum biogas yield through co-digestion of cassava biomass, vegetable and fruits at different ratios in a single stage fed-batch anaerobic digester for biogas production. The physical pre-treatment of the both substrates was by milling the feedstock into small pieces prior to anaerobic fermentation. Anaerobic digestion of the mix of cassava biomass and vegetable & fruit was investigated in a 600 ml digester for 31 days under mesophilic condition (37ºC). Bio-methane potential of cassava biomass co-digested with vegetable & fruit ranged from 1124.26 to 1641.82 mL CH_4/g VS. Co-digestion of CB and VF with inoculum at ratio of 40:60 achieved the maximum methane yield of 1641.82 mL/g VS which was 23.08% higher than that of the mono-digestion feedstock.

Keywords: Anaerobic digestion; Gompertz model; Performance Index; Mon-digestion; Vegetable & Fruit.

6.1 INTRODUCTION

The increase in urbanization and human population growth has resulted in an increase of demand for services such as electricity and waste management (Madlener and Sunak, 2011). According to FAO (2017), in South Africa, urban population (65.8%) is approximately twice the rural population (34.2%) as indicated in Figure 6-1. In 2012, the urban population was approximately 63.3% and rural population was 36.7%, this figure shows an increase of 2.5% between 2012 and 2017. Though the increase seem insignificant it is important that the government prepares for the growth well in advance. The population growth implies that the energy demand for both urban and rural communities will also be on the increase (Madlener and Sunak, 2011). This implies that the energy demand for urban area will also be on the increase. Biomass from fuelwood and charcoal forms the dominant source of energy in African countries with South Africa inclusive (Wessels et al., 2013).

Presently, most rural municipalities power most of the communities under their jurisdiction using candles, paraffin’s as well as fire gel. It is reported that in 2016, about 16.6 million households make use of candles for lighting. Based on available statistics, over 86 500 poor households have access to free paraffin in 20 municipalities. Majority of these communities are concentrated in Eastern Cape and Northern Cape, with two municipalities in North West. These sources of energy are not clean and cost effective. They can simply be replace by electricity from biogas (Stats, 2019).

There is a lack of clean energy in South Africa as about 74.8% of energy come from coal (Amigun et al., 2012) which is not environmentally safe. With the increase in urban population, still half a million people within South Africa still do not have access to electricity within their homes (Jamal, 2015). According to Brown (2006), homes with no electricity to meet their cooking demands have to rely on fuelwood/firewood and that has been an hindrance to development in those areas.

Biogas that forms part of the renewable energy is being mostly used in developed and some developing countries such as Asia to meet some of their energy needs (Surendra et al., 2014, Peres et al., 2018). South Africa could make use of renewable energy to reduce the dependence on fossil fuels which have both health and environmental consequences.

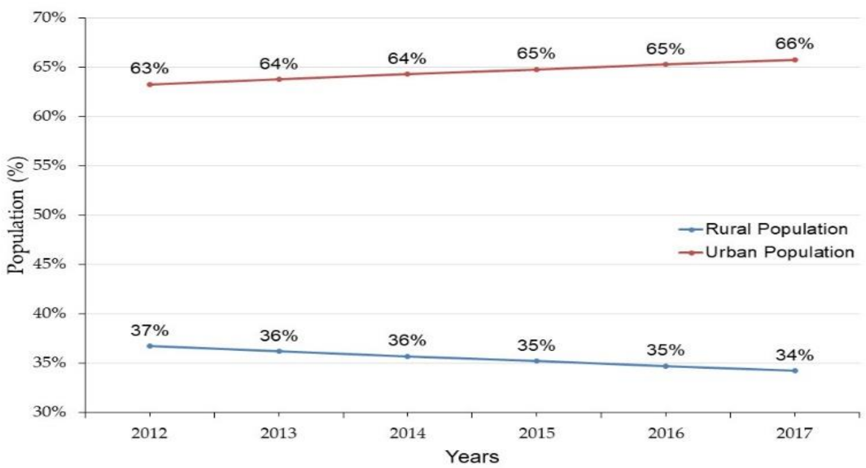


Figure 6-1: Rural and Urban Population from 2012 to 2017 (Faostat, 2018)

According to Quadrelli and Peterson (2007), South Africa is grouped among the top emitters of Green House Gases (GHGs) worldwide. Therefore, there is a need for

South Africa to decrease its carbon intensity. This can be partly achieved through the adoption of biogas technologies. In the process of decreasing the carbon intensity, the country will be fully and simultaneously exploring renewable energy and improving the life of the citizen of the country. Table 6-1 shows some of the areas in which biogas has been applied in South Africa.

Table 6-1: Location of Biogas Application in South Africa (Bond and Templeton, 2011)

Application	Location	Discussion
Agricultural	George	Private client using biogas to supply energy at their farm
Sewage Treatment Works	Elim	Biogas generated using sewage treatment works and the dairy farm
Industrial	Cape Flats	Treatment of sewage sludge and generated biogas used for heating of the digester.

Energy crops are considered to be traditional agricultural crops grown typically for food. However due to the crop characteristic, it has been considered for energy production (López-Bellido et al., 2014). There has been some agitation on the use of energy crop for energy generation because it may affect the food chain and access to food. In order to mitigate conflict of interest caused by this agitation, the waste products or non-edible parts of energy crop can be used for energy generation, while the edible parts can be used for food production. Alternatively, the growing of energy crop on marginal land can be encouraged, therefore making the crop unsuitable for food crop production. For instance, though the production of energy crop like cassava is low in South Africa, using it as capping crop for landfill would enable its planting on landfills for the sole purpose of energy generation. This is because the landfill capping crop has low biodiversity and economic value as there is a high risk of the cassava absorbing toxic trace element which could pose health risk to human. Cassava biomass has many benefits such as biogas production, since it contains large amount of fermentable sugar (Okudoh et al., 2014).

The chemical and physical characteristic of feedstock plays an important role in the anaerobic process. Therefore, the performance of the digester and the quality of the biogas yield is influenced by the composition of the substrates used. With regards to this research area little research has been conducted in South Africa. The aim of this study is therefore to determine the biogas yield of mono and co-digestion of vegetable & fruits and Cassava in a controlled mesophilic environment by means of a batch reactor. This study determines the optimum biogas yield of cassava through co-digestion.

6.2 MATERIALS AND METHODS

6.2.1 Cassava Biomass and Vegetable & Fruits waste collection

The cassava (*Manihot esculenta Crantz*) biomass (200 kg) used for this study were obtained from cassava plantation in the *"Nampula"* Province of Mozambique, while the Vegetable & Fruits waste (VF) (200 kg) were obtained from farm in a small town "Verulam" in KwaZulu-Natal. Both substrates were collected into a plastic bag and stored in a refrigerator at 4 ˚C to preserve the freshness. The physical characteristics of the used substrates are presented in results and discussion section 6.3.

6.2.2 Inoculum

The inoculum used for this study was fresh cow dung (CD) which was collected from *"Ukulinga"* Research Farm, Pietermaritzburg, South Africa. CD was used because of its high buffering capacity including its richness in the required microbes that is essential for the anaerobic digestion process. The CD used was characterized and results presented in section 6.3 (Results and Discussion).

6.2.3 Substrate Preparation

The cassava biomass

Approximately one hundred kilogrammes (100 kg) of the collected fresh cassava tuber was mechanically pre-treated by peeling, while the remaining 100 kg of the fresh cassava was stored for later use. The peeled cassava was washed with tap water and chopped into pieces of about 1 cm^3 using a sharp knife after which it was sundried for 2 days. The sundried cassava biomass were milled with a scientific Republic of South Africa hammer mill that is equipped with a 1 mm sieve mesh to obtain the cassava flour. The prepared milled cassava biomass were stored in a refrigerator at 4 ˚C until use. The properties of the substrates are shown in section 6.3 (Results and Discussion).

The Vegetable and Fruit Waste

The collected vegetable and fruit waste was collected randomly different parts of the volume to be sampled. Sampling of the fruit & vegetable was done following the suggestion of Sitorus and Panjaitan (2013), whereby the waste were taken based on the grab sampling method with the feedstock composition having a ± 80% vegetable waste and a ± 20% fruit wastes (Figure 6-2). A total of 160 kg were collected after which these samples were mixed together. Coning and quartering method was used to reduce the size of the mixed samples. The samples were dried at 60°C in an oven until constant weight. Milling was performed with a scientific RSA hammer mill to reduce sample particle size to < 1mm after which a laboratory blender were used for size reduction. The prepared samples were labelled and packed in plastic sample bags and stored at 4°C for analysis.

Figure 6-2: Vegetable and Fruit

Cow Dung Innoculum

Fresh Cow Dung (CD) collected from *"Ukulinga"* Research Farm was used as an inoculum to start up the experiment (Figure 3). The sample of CD was collected in sterile plastic bags and was kept in an airtight container at 4 °C; prior to use. Before utilization the CD was acclimatized and degassed at 37 °C for 1 week to minimize the production of methane from the inoculum (Liew, 2011). The inoculum was prepared by soaking CD with deionized warm water to a of 1:1 ratio (Figure 6-3B). It was thereafter sieved through a cloth of 0.5 mm to separate the solid content from the slurry. The characteristics of the substrates used in this study (i.e. CB, VF and CD) are shown in section 6.3 (Results and Discussion).

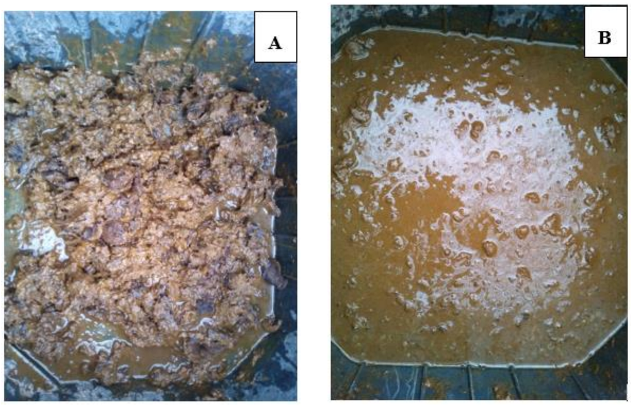


Figure 6-3: Cow Dung from Ukulinga Research Farm A) sampled cow dung, B) cow dung with deionized water

6.2.4 Experimental set-up

A batch system configuration was used when conducting bio-methane potential (BMP) for this study. The study was conducted under controlled conditions at mesophilic temperature 37˚C ± 0.5. Four stage experimental design which consist of four (4) ratios namely 100:0, 60:40, 40:60 and 50:50 as shown in Table 6-2 were used and three runs were conducted. The BMP was conducted in a 600 ml SCHOTT DURAN® glass laboratory bottles (bio-digesters) (Figure 6-4). The bio-digester was filled to 80% of its capacity, which signifies 480 ml working volume. The bio-digester was submerged into a water bath to which it had a heating element to keep the water bath at constant temperature of 37˚C ± 0.5 for the duration of the experiment.

A total solids of 8% (Ituen et al., 2009) was used to obtain a better biogas yield. This was achieved by mixing feedstock with tap water to get to the 8% TS. The amount of water to be added to the feedstock was calculated using the below formula:

$$Amount\ of\ water = \frac{A}{B+C} \qquad (6\text{-}1)$$

Where:

A = Mass of fixed total solids

B=Mass of fresh Cassava Biomass + Mass of Vegetable & Fruits waste

C=Mass of water to be added to achieve 8% total solids in digester

Table 6-2: Biochemical Methane Potential Experimental Design

Digester	Mix Ratio		TS of CB (g)	TS of VF (g)	Contents of the digester				Total Volume (mL)
					Amount of Fresh Substrate		Amount of Water added (mL)	Amount of Inoculum added (mL)	
	%CB	%VF			CB (g)	VF (g)			
R+	-	-	-	-	-	-		480	480
A+	100	0	30.5	0	32.64	0	347.36	100	480
B+	60	40	18.3	12.2	19.58	29.33	331.086	100	480
C+	40	60	12.20	18.30	13.06	43.99	322.954	100	480
D+	50	50	15.25	15.25	16.32	36.66	327.02	100	480
E+	0	100	0	30.5	0	41.75	321.47	100	480
A*	100	0	30.5	0	32.64	0	447.36	0	480
B*	60	40	18.3	12.2	19.58	29.33	431.086	0	480
C*	40	60	12.20	18.30	13.06	43.99	422.954	0	480
D*	50	50	15.25	15.25	16.32	36.66	427.02	0	480
E*	0	100	0	30.5	0	41.75	421.47	0	480

CD: Cow Dung, CB: Cassava Biomass, VF: Vegetable & Fruit waste, R: bio-digester, A* - E*: No inoculum added, R+: control (Inoculum only) and A+ – E+: inoculum added

After preparing the substrate and the inoculum the bio-digesters were filled up with the feedstock (inoculum and substrates) as per Table 6-2 above. The pH was measured using and adjusted were necessary to pH 7 using 1M (1 molar) sodium hydroxide (NaOH) solution before the commencement of the anaerobic digestion process. Liquid displacement method was used to measure the biogas yield (Figure 6-4).

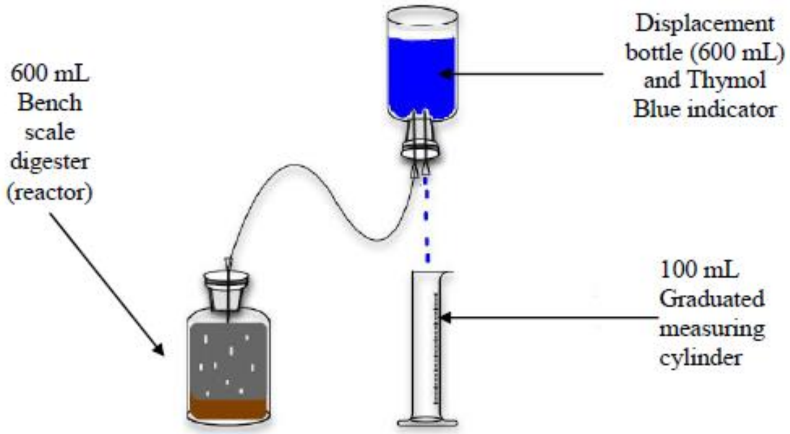


Figure 6-4: Schematic diagram of experimental laboratory set (Tawona, 2015)

6.2.5 Experimental Procedure and Analytical Methods

The bio-digesters were flushed with nitrogen gas for 2 minutes by removing all dissolved oxygen and to set anaerobic conditions and thereby sealing the bio-digester bottles with a plugged with tight rubber plugs to prevent escape and inflow of gas into the bio-digester. To prevent scum accumulating and achieving homogeneity in the bio-digester it was manually shake twice a day at 1pm and 5pm daily.

All the bio-digesters were inoculated with cow dung except for digester A* to E* as shown in Table 6-2. A 100 ml inoculum was used on digester A^+ to E^+. A blank digester filled with inoculum and water was used as a control digester (R^+). The control digester consisted of 100 ml inoculum and 380 ml water. This served as a control bio-digester which will form the baseline for all the other co-digestion.

Digester B^+ which consisted of a 60:40 (CB:VF) ratio 160 ml of VF was inoculated with CD, C^+ was feed with 160 ml CB and inoculated with CD, while lately D^+ was filled with 80 ml VF and 80 CB and 240 ml CD. Digesters A^+, E^+, A* and E* consisted of mon-digestion were A+ and E+ had CB (100:0 ratio CB:VF) only with inoculum added while A* and E* has VF (0:100 ratio CB:VF) only with no inoculum added. The BMP experiment was carried out for a duration of 40 days before it was terminated.

The total solids (TS) and volatile solids (VS) in the feedstocks and inoculum were analysed using standard techniques at the beginning (Federation and Association, 2005) of the AD process and at the end of the 40 d incubation period (APHA, 2005). TS content was determined after drying the sample in an oven overnight at 105 °C.

VS content was calculated as TS minus the ash content after ignition at 550 °C in a muffle furnace.

6.2.6 Biogas Yield Calculation

The biogas yield was measured by using the water displacement method. As the biogas is generated in the bio-digester it is transported by a plastic pipe into the displacement bottle which generates pressure within the displacement bottle thereby forcing water up into a 100 ml graduated measuring cylinder.

The bio-digester is kept air tight, thereby preventing the escape of biogas. The biogas produced by the co-digestion substrate was calculated by subtracting the biogas formed by the inoculum only from that of the biogas formed by the co-digestion substrate (Equation 6-2).

$$Y_1 = Y_{0+1} - Y_0 \tag{6-2}$$

Where:

$Y_1 = Net\ Biogas\ Produced\ Daily\ (ml)$

$Y_{0+1} = Biogas\ Produced\ from\ co - digestion\ substrate\ Daily\ (ml)$

$Y_0 = Biogas\ Produced\ from\ control\ substrate\ Daily\ (ml)$

The cumulative biogas yield was calculated by summing daily yield, and then the cumulative methane yield was calculated by dividing the net cumulative methane by the mass of the volatile solid added (Equation 6-3).

$$X = \frac{X_1}{Z} \tag{6-3}$$

Where:

$X = cumulative\ methane\ yield\ \left(ml\frac{CH_4}{gVS}\right)$

$X_1 = Net\ cumulative\ methane\ (ml\ CH_4)$

$Z = Mass\ of\ Volatile\ Solid\ added\ (g)$

1.1. *The Gompertz Model*

Equation 6-4 represents the modified Gompertz model that describes the cumulative biogas production curve in batch operated digester, this equation assumes that the substrate levels limit growth in a logarithmic relationship (Pell et al., 1994). The modified Gompertz Model was applied to compare the model predication and the experimental data. This model was applied on the cumulative methane yield.

$$y(t) = y_m \exp\left\{-\exp\left[\frac{Ue}{y_m}(\lambda - t) + 1\right]\right\}, t \geq 0 \qquad (6\text{-}4)$$

Where:

y_m = biogas yield potential (Lkg-1 VS),

y(t) = cumulative biogas at digestion time t days (Lkg-1 VS),

U = the maximum biogas production rate (Lkg-1 VS. day),

λ = lag phase period or minimum time to produce biogas (days),

t = cumulative time for biogas production (days),

e = mathematical constant (2.718282),

6.2.7 Co-digestion Performance Index (CPI)

The performance of combined substrates was investigated to determine the effects which maybe the dilution and/or enhancement of performance by adding valuable nutrients. These nutrients could increase the bio-degradability thereby changing the microbiome to either increase the performance and/or decreasing it (Wang et al., 2018). The optimal mixture composition between two substrates have been investigated in several studies (Pagés-Díaz et al., 2014, Astals et al., 2014). A CPI > 1 indicates that there is a synergistic effect of the co-digestion while CPI < 1 shows that there is an aggressive effect (Labatut et al., 2011). According to Ebner et al. (2016) the co-digestion performance index (CPI) was calculated using Equation 6-5:

$$CPI_{i,n} = \frac{B_{i,n}}{B_{oi,n}} = \frac{B_{i,n}}{\sum_i^n \%VS_i B_{o,i}} \qquad (6\text{-}5)$$

Where:

$CPI_{i,n} = Co - digestion\ Performance\ Index$

$B_{i,n} = bio - methane\ potential\ of\ the\ co - digestion\ blend$

$B_{oi,n}$
$= co$
$- digestion\ blend\ to\ the\ weighted\ average\ (\overline{B_{oi,n}}) based\ on\ the\ VS\ content\ (\%VS) of\ the\ indivial\ s$
$- substrate\ bio - methane\ potential$

6.3 RESULTS AND DISCUSSION

6.3.1 Substrates and inoculum Characterization

Table 6-3 shows the characterization of substrates and inoculum. Characterization is one of the most important steps in the anaerobic digestion as it gives the general composition of the substrate (feedstock). It can be used to calculate the amount and composition of the biogas produced, including the energy content in the biogas. The characterization of the substrates and inoculum shows the physical and chemical characteristics of CB, VF and CD. CD inoculum had higher TN and lower TC compared to cassava biomass and vegetable & fruits waste. The mixture of each other could complement each other to achieve the suitable co-digestion nutrient content.

Table 6-3: The composition of cassava biomass, vegetable & fruits and inoculum

Proximate and Ultimate Analyses	Substrate		Inoculum (Cattle Dung)
	Cassava Biomass	Vegetable & Fruits Waste (VF)	
Moisture Content (%)	66.15 ± 1.01	58.40 ± 0.61	83.50 ± 0.16
Total Solids (%)	93.45 ± 0.21	41.60 ± 0.22	19.84 ± 0.51
Volatile Solids (%)	97.02 ± 0.52	76.10 ± 0.67	12.40 ± 0.57
Protein	2.35 ± 0.11	77.30 ± 0.91	-
Total Nitrogen (%)	0.55 ± 0.12	0.52 ± 0.28	2.06 ± 0.18
Total Carbon (%)	39.7 ± 0.61	39.06 ± 0.84	38.12 ± 0.81
C/N Ratio	72.18	75.12	18.50
Ash (%)	1.75 ± 0.11	9.44 ± 0.17	30.40 ± 0.15
Calcium (%)	0.02 ± 1.12	0.14 ± 0.19	0.42 ± 1.19

Proximate and Ultimate Analyses	Substrate		Inoculum (Cattle Dung)
	Cassava Biomass	Vegetable & Fruits Waste (VF)	
Starch (%)	76.32 ± 2.01	ND	ND
Sugars	77.54 ± 1.11	42.87 ± 1.01	ND

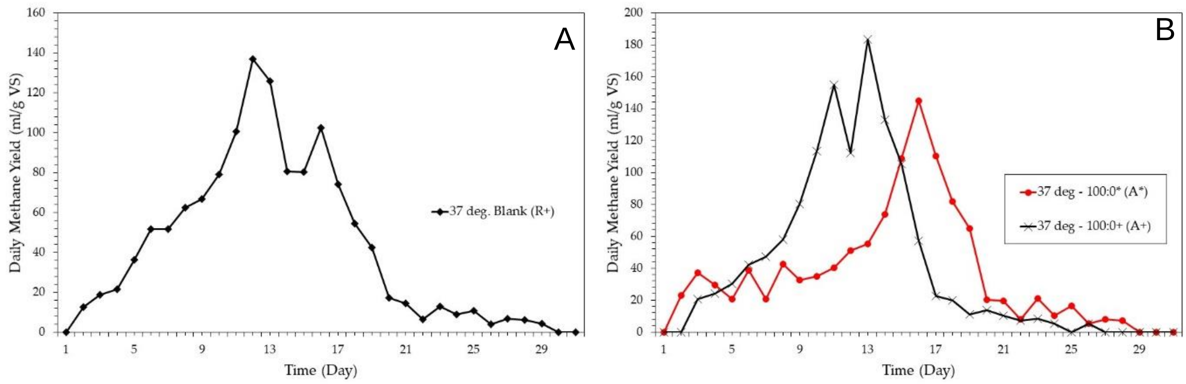
ND: Not determined

The total solids of both substrates and inoculum is between 19.84% - 93.45%, with the cattle dung having the lowest total solids of 19.84% and the CB with the highest of 93.45%. These are in contradiction to what was reported by Malakahmad et al. (2009) who stated that for biogas production, the solid content of the feedstock should be between 10% – 15%. The total solids content has great impact on cumulative biogas. According to Liu et al. (2014) the cumulative biogas decreases with an increase of total solids content from 5% to 10%. However, the cumulative biogas further increased subsequently as the total solids increased beyond 10%.

The inoculum had the lowest carbon to nitrogen (C/N) ratio of 18.50 and cassava biomass (Mcbride, 2012) with the greatest of 72.18. C/N ratio plays a critical role in the performance and/or yield of biogas. The C/N ratio in the anaerobic digestion should be within the optimal range of 20-30 for optimum performance of the digester (Li et al., 2011, Li et al., 2016), as bacteria in the digester uses up carbon 25-35 times faster than compared to that of using up nitrogen (Sitorus and Panjaitan, 2013). The C/N ratios of CB and VF were above the maximum limit of 30 which is an indication of rapid consumption of nitrogen at methanogens stage which results in the low production of gas. The C/N ratio of the CD however was under 20 which causes accumulation of ammonia and an increase in pH level which becomes toxic to the methanogenic bacteria (Tanimu et al., 2014) . Therefore, co-digestion could be used to balance substrate with high C/N ratio using substrate with low C/N ratio such as cattle manure which are easily available and suitable for renewable energy (Wu et al., 2010). Vegetable waste has significant limitation due to its rapid acidification as a result of its low pH level and the high production of volatile fatty acids which affect the methanogenic activities in the digester. The moisture of all substrate CB and VF was found to be 66.15% and 58.40% respectively. This indicates that the disposal of both substrates were not ideal for landfilling and incineration due to its high moisture content (Girotto et al., 2015).

6.3.2 Daily and cumulative methane yield at mesophilic (37˚C) temperature

Figure 6-5 shows the daily methane yield of all the digesters. It can be observed that the methane yield of the blank substrate and single digestion increased gradually (Figure 6-5A – Figure 6-5C). The co-digestion (Figure 6-5D – Figure 6-5F) started to produce biogas on day one, with co-digestion of cassava biomass and vegetable & fruits waste without inoculum (CB: VF) at 40:60* ratio producing the highest methane on day one of 59.68 ml/g VS. The maximum methane yield peak (220.55 mL/g VS) was reached on the twelfth day. It was reached by the co-digestion CB: VF at a ratio of 50:50 (Figure 6-5E). The next highest was followed by co-digestion CB: VF (Figure 5F) at a ratio of 40:60 (211.09 mL/g VS). The methane yield of all the co-digestion feedstock (Figure 6-5D – 6-5F) decreased significantly after day one. This could be attributed to the acidification in the batch reactors which confirms that hydrolysis and the alcoholic fermentation of the vegetables waste are rapid compared to other organic substrates (Sitorus and Panjaitan, 2013, Di Maria et al., 2014).



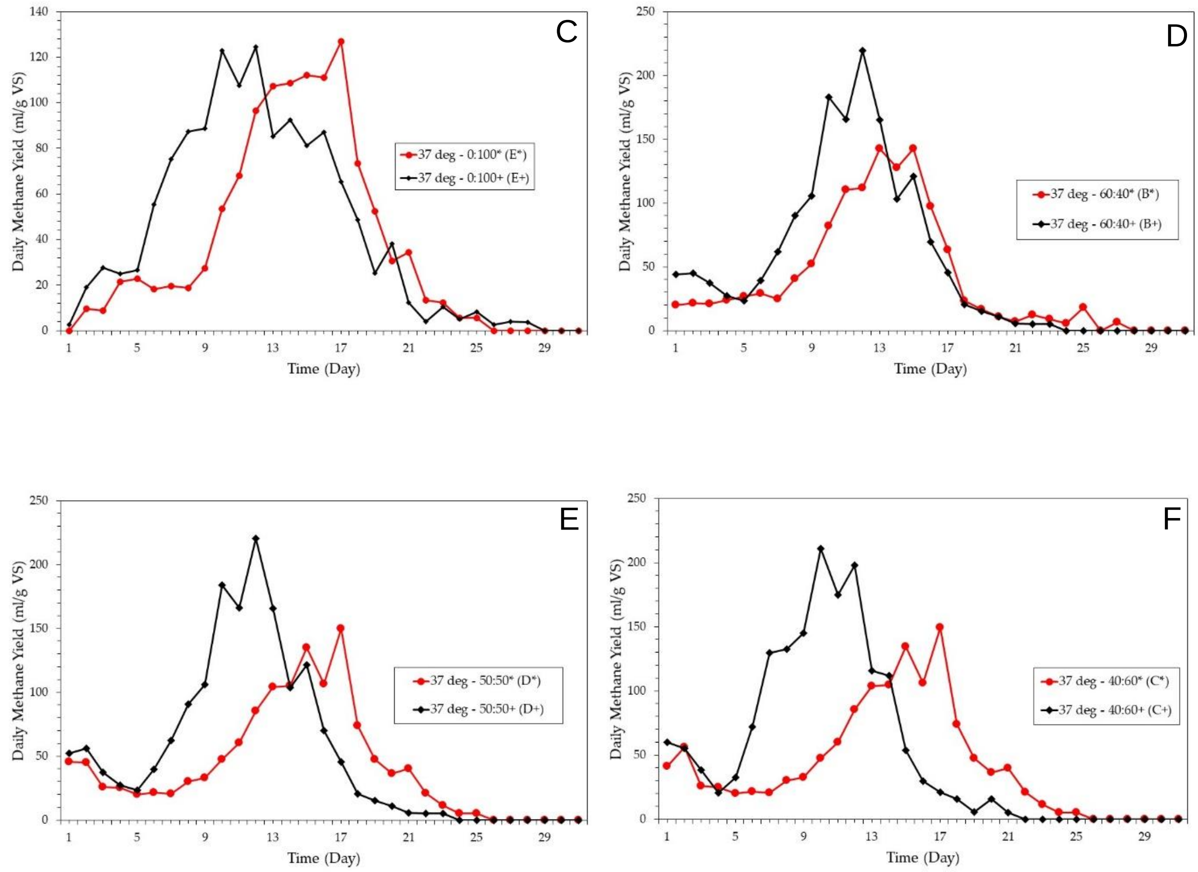
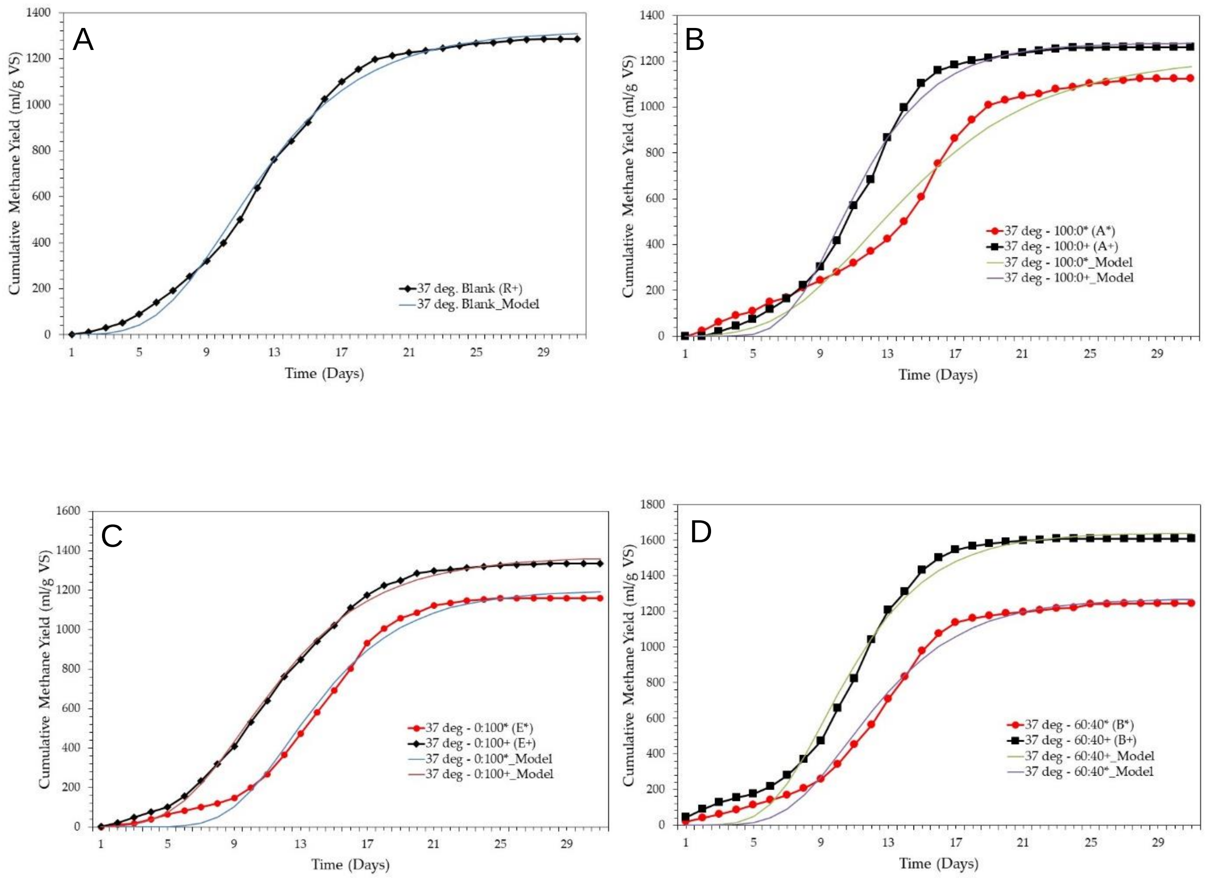


Figure 6-5: Daily Methane yield at 37°C of A) Blank no inoculum, B) single digestion of Cassava tuber and vegetable & fruit, C) co-digestion of Cassava tuber and vegetable & fruit at 60:40, D) co-digestion of Cassava tuber and vegetable & fruit at 60:40, (E) co-digestion of cassava tuber and vegetable & fruit at 50:50, (F) co-digestion of Cassava Tuber and vegetable & fruit at 40:60, ; "+" – with inoculum, "*" – without inoculum

Figure 6-6 shows the cumulative methane yield (CMYs) of mono-digestion and co-digestion at different ratios. Cassava single digestion without inoculum (Figure 6B) produced the lowest cumulative methane yield (1124.26 mL/g VS) compared to mono-digestion of cassava with inoculum (1262.90 mL/g VS). Co-digestion of CB : VF with cattle dung inoculum at a 40:60 ratio (Figure 6-6F) produced the highest cumulative methane (1641.82mL/g VS) due to more available substrate, It confirms that biogas yield could be improved by co-digestion of the suitable substrate (Zamanzadeh et al., 2017). However, the ratio mix ratio of the substrate is of importance as this could change the digestion process in the digester thereby changing the biogas yield and the rate (Li et al., 2016). When the cassava biomass ratio was reduced and the ratio of the vegetable & fruit waste was increased, the cumulative methane yield increased proportionally.

The percentage increase of the cumulative methane yield of co-digestion CB:VF (40:60) in relation to the mono-digestion of cassava at a ratio 100:0 (CB:VF) is 13.65%. These implies that co-digestion does enhance performance of the digester for maximum yield. It should be noted that when the co-digestion of CB:VF ratio increase from 40:60 to 50:50 the cumulative methane yield was negatively affected; suggesting that an increase of CB in relation to the VF would reduce the methane yield. It could be observed that the methane yield deceased by 1%.

These results suggest that the suitable co-digestion proportion of CB and VF for maximum methane yield is 40:60 as the highest methane production of 1641.82 mL/g VS was achieved.



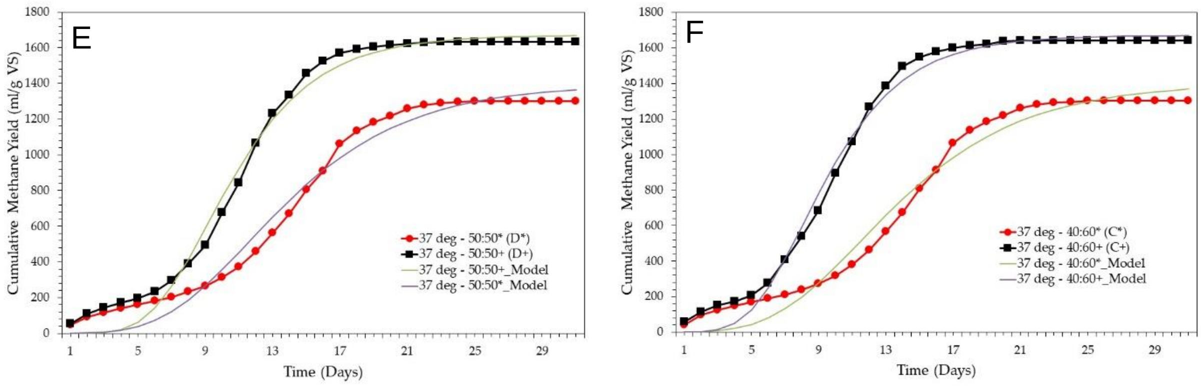


Figure 6-6: Cumulative methane yields with (A) Blank inoculum only, (B & C) single digestion of Cassava tuber and vegetable & fruit, (D) co-digestion of Cassava tuber and vegetable & fruit at 60:40, (E) co-digestion of cassava tuber and vegetable & fruit at 50:50, (F) co-digestion of Cassava Tuber and vegetable & fruit at 40:60, ; "+" – with inoculum, "*" – without inoculum

6.3.3 The Gompertz Model

The parameters such as y_m, λ and µ of Gompertz Model were obtained by fitting the equations to the experimental biogas yield data. Table 4 presents the summary of the results of both experimental and predicted biogas yield calculated using the Gompertz Model coefficients at day 31. The experimental methane yield was modelled using Gompertz Model and presented Figure 6-6. These models can be used to estimate the biogas yield at any given time under a specific condition.

Referring to Table 6-4, the substrate of co-digestion of CB:VF with inoculum yielded more y_m with a maximum biogas yield of 1671 $Lkg^{-1}VS$ compared to the other substrate, the lowest was obtained from mon-digestion of VF without inoculum. This results confirmed the finding of Rodriguez-Chiang and Dahl (2014) that inoculum improves the biogas yield of substrates. All the substrates that were inoculated performed better than that without inoculum. The biogas yield from the model, predicted and also measured shows that the ratio of 40:60 yielded the maximum biogas. These results confirm that vegetable and fruits has certain properties that improved the performance of digester to yield maximum biogas as reported by Phetyim et al. (2015).

Table 6-4: The coefficients and constants developed by fitting the modified Gompertz to cumulative methane yield data

Digester	Ratio	Modified Gompertz Model			Predicated biogas yield ($Lkg^{-1}VS$) - 40 d	Measured biogas yield ($Lkg^{-1}VS$) - 40 d	Difference between measured and predicted biogas yield (%)
	CB:VF	λ (days)	µ ($Lkg^{-1}VS.day$)	ym (L/kg VS)			
R^+	Blank	10.36	0.23	1320	1308.6	1287.3	1.65%
A*	100:0	12.01	0.18	1216	1175.5	1124.2	4.56%
B*	60:40	10.63	0.27	1274	1268.5	1246.2	1.79%
C*	40:60	11.53	0.19	1403	1368.7	1302.1	5.11%
D*	50:50	12.53	0.19	1397	1365.2	1300.2	5.00%
E*	0:100	12.38	0.27	1199	1190.6	1157.7	2.84%
A^+	100:0	10.03	0.32	1280	1278.3	1262.9	1.22%
B^+	60:40	9.27	0.29	1642	1639.3	1607.8	1.96%
C^+	40:60	8.10	0.31	1671	1669.5	1641.8	1.69%
D+	50:50	9.16	0.29	1671	1667.7	1632.7	2.14%
E^+	0:100	9.62	0.23	1368	1358.6	1335.7	1.71%

+: with inoculum; *: without inoculum

6.3.4 Co-digestion Performance Index (CPI)

From Figure 6-7, it can be observed that the CPI of the co-digested substrates range between 1.092 (for, 60:40*) and 1.264 (for, 40:60+). These show that the co-digestion of the substrate has a positive synergistic effect since the CPI is greater than one (CPI > 1). Co-digestion of cassava biomass and vegetable & fruit waste residues with inoculum showed higher methane yields (1641.82 mL/g VS) which is supported by the CPI of 1.264.

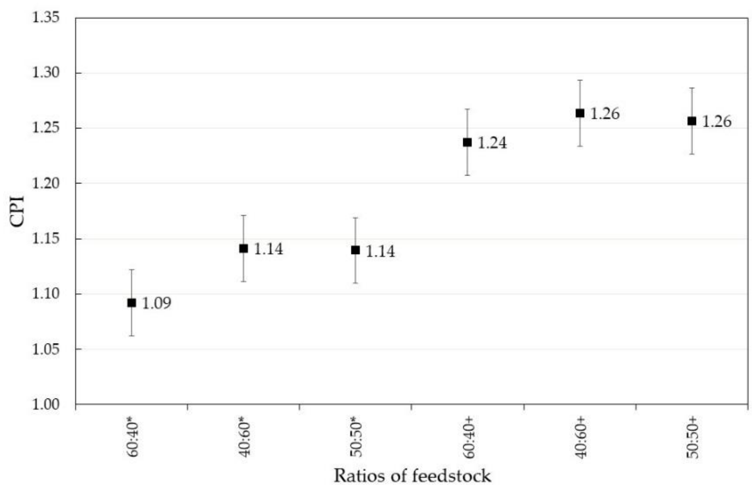


Figure 6-7: Co-digestion Performance Index (CPI) of co-digestion at different mixture ratios, CPI > 1 indicates synergistic effect, CPI < 1 indicates antagonistic effect. Different ratios (Cassava Biomass: Vegetable & Fruits)

When the proportion of cassava biomass was higher to that of the vegetable & fruit waste (60:40*), the CPI decreased with the increase in the cassava biomass. Both ratios (60:40* and 60:40+) of cassava biomass to vegetable & fruit waste without and with inoculum had a CPI of 1.092 and 1.237 respectively.

The lowest CPI came from the co-digestion of CB and VF without inoculum to a ratio of 60:40*. These results suggest that the increase in ratio of cassava biomass could negatively affect the co-digestion performance.

According to Wang et al. (2012), several factors could impact the synergistic effect, factors such as balanced nutrient composition, stimulated synergistic effects of microorganisms, an associated increase in buffering capacity, and a decreased effect of toxic compounds on the digestion process.

6.4 CONCLUSION

The determination of biogas yield of mono and co-digestion of vegetable & fruits with cassava in a control mesophilic environment by means of a batch reactor has been carried out. The characterization of the cassava biomass and the vegetable & fruit waste indicated that they have high biogas potential with the cassava biomass having a high carbohydrate. The carbon to nitrogen (C/N) ratio was significantly high with

72.18. To balance the C/N ratio, co-digestion with animal manure was performed to make the C/N to be between 20 and 30. Cassava biomass co-digested with vegetable & fruit waste was successful in producing methane. However, cassava biomass mono-digestion produced the lowest methane yield. The maximum methane yield of 1641.82 mL/g VS was obtained from the mixture of CB and VF with cattle dung inoculum at a ratio of 40:60 which was 23.08% higher than that of the mono-digestion feedstocks. In conclusion, cassava biomass co-digested with vegetable & fruit waste to a ratio of 40:60 was a good substrate for methane production. Cassava biomass mono-digestion yielded the lowest methane yield. The maximum methane yield of 1641.82 mL/g VS was obtained from the mixture of CB and VF with cattle dung inoculum at a ratio of 40:60 which was 23.08% higher than that of the mono-digestion feedstock. In conclusion, the optimal conditions for maximum yield of biogas of cassava biomass co-digested with vegetable & fruit waste were: initial pH of 6.87, ratio of CB:VF at 40:60 and temperature at 37 °C, for maximum yield inoculum should be used to start the digestion process in the digester. This research can serve as a frontier for the development of a biogas plants location map across South Africa. Finally, before the proposed system can be adopted on a large scale, it is essential to carry out further investigation at pilot level using specific cassava tuber from landfill.

CHAPTER 7:

BIOGAS TECHNOLOGY AND THE DESIGN OF HOUSEHOLD DIGESTER FOR CO-DIGESTION OF CASSAVA AND VEGETABLE & FRUITS WASTE

PREFACE

Based on the promising results obtained in chapters 4, 5, and 6, a pilot fixed dome digester was designed to yield 0.25 m^3/person/day for cooking purposes. Chapter 7 aims at presenting the process followed in sizing the digester to meet the energy demand for five (5) families; each comprising eight (8) members.

This chapter is written in the form of a journal article to be submitted to *International Journal of Mechanical Engineering and Technology (Scopus)*, minor changes were made to improve its reading. The detailed drawings with dimension of the digester can be found in Appendix D1.

ABSTRACT

Global increase in energy demand has given rise to the need to harness the potential of renewable energy sources. Biogas production from waste has been identified as one of the sustainable renewable energy technologies with great potential for energy production and has been argued to be one of the pathways to solving South Africa's energy problems. Successful implementation of waste-to-energy (biogas generation) projects is however dependent on a number of factors which include, but are not limited to, digester type and configuration, digester size and, more importantly, availability of substrate. This paper presents the design of an anaerobic digester for sustainable co-digestion of cassava, vegetable and fruit waste. Using a scenario-based approach, the digester was designed to produce biogas energy that will cater for five (5) families; each comprising eight (8) members. Given an energy requirement of 0.25 m^3/person/day for cooking purposes, the biogas production rate of the digester was estimated to be 10 m^3/day. Additional parameters such as active slurry volume, volume of gas storage, height and diameter were calculated using mathematical calculations via scaling up of experimental data. A fixed dome configuration coupled with a mesophilic temperature profile were adopted in designing the digester. The dimensions of the digester to achieve the energy requirement were Height of Cylindrical Digester (H) 2.09 m, Diameter of Digester (D) 4.19 m, Breadth of inlet and outlet (b) 1.54 m, Dome height (d_h) 0.829 m and Radius of Dome (r) 3.06 m at an estimate cost of R 121 136.09 (material only).

Keywords: Bio-digester; Mesophilic; Fixed Dome; Gas Production Rate; Vegetable & Fruit.

7.1 INTRODUCTION

Fossil fuel is currently the world's main supply of energy and is prevalent in forms such as coal, crude oil, natural gas and lignite. Such fuels are not renewable in nature as they were formed millions of years ago but are consumed at a much faster rate than they are formed (Al Seadi et al., 2008). Many economies are thus investigating sustainable energy systems that are environmentally friendly, clean and adaptable. Biogas is currently being considered as a renewable energy resource that could possibly serve as a viable alternative to fossil fuels, especially in developing economies like Africa where majority of its population lacks access to constant energy supply, and consequently, depend on imported energy (Amigun et al., 2012, Owusu and Asumadu-Sarkodie, 2016).

Biogas is generated through the anaerobic digestion of organic matter, whereby the substrate is converted into renewable energy (Ye et al., 2013, Ošlaj and Muršec, 2010). Biogas contribute to the global energy mix hence it is considered as an energy carrier (Braun et al., 2008, Jingura and Kamusoko, 2017). The conversion occurs in an anaerobic digester which is also known as biogas digester. Several research has resulted in various designs of biogas digesters which range from simple to sophisticated, depending on the budget and the end use of the biogas (Anozie et al., 2005). According to Anozie et al. (2005), as the level of sophistication in terms of design increases, the demand for manpower with suitable skills increases, making its implementation a challenge due to shortage of such skills.

Various digester types have been developed over the last century. Based on flow configuration, digesters can be categorized as: (1) batch flow, (2) continuous flow, (3) continuously expanding, (4) plug flow, and (5) contact flow (Samer, 2012). Digesters that process liquid raw material that has high solids content are called “conventional digester” or “rural digester”. These kinds of digester have fermentation chamber volume of less than $100m^3$ (Florentino, 2003). The conventional digesters however do not have any mechanism to reduce the retention time, making the feedstock biomass to remain in the fermentation chamber until the biogas yield reduces. These systems are fed using a stage-wise approach, making it a batch digester. Considering the high profile of socioeconomic challenges plaguing developing countries, the need for simple, distributed and cost-efficient digester designs is of great importance to foster the adoption of waste-based renewable energy sources (Singh and Harvey, 2010).

Biogas can be produced from various substrates, such as cow dung, poultry droppings, cassava biomass, vegetable and fruit waste as well as their mixture. As reported in Jordaan (2018), since the introduction of the first biogas digester in 1957 (Esi-Africa, 2016), South Africa has only about 700 biogas digesters installed (Cheng et al., 2014). We however posit that South Africa could increase the number of biogas installations if cassava biomass co-digested with vegetable and fruit waste is adopted.

To this end, the main objective of this paper is to design a low-cost biogas digester based on the optimum production results obtained from initial experimental results (chapter 6). The task involves designing all system components of the biogas digester namely inlet and outlet chambers, dome height, digester (fermentation chamber) and agitator/impeller (Figure 7-1). The following sections presents a synopsis of available biogas installations in South African followed by a step-by-by approach for the design of the proposed biogas digester.

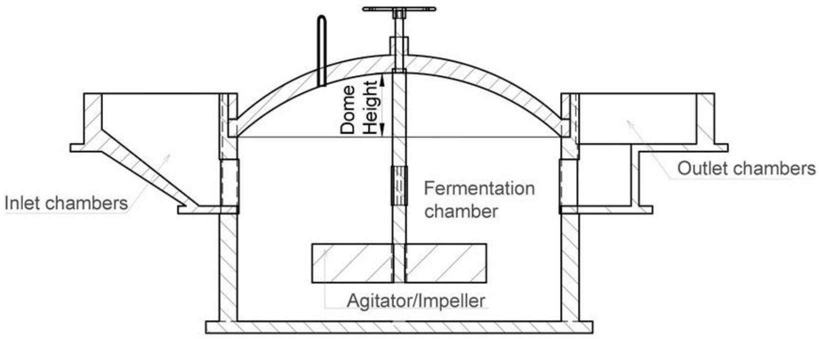


Figure 7-1: Key components of biogas digester

7.1.1 Type and location of installed biogas digesters in South Africa

Several digesters have been designed and installed in different areas in South Africa since the initiation of the biogas technology in 1957 (Table 7-1). The biogas digesters in different parts of South Africa were installed by different organizations with three current projects being executed in local communities namely: Melani village biogas expansion, Ilembe district and Mpufuneko biogas projects. Most of the digesters (medium to large scaled) were installed between the years of 2005 to 2017. Although some small domestic digesters may have been developed and installed by some private individuals, there are however no published records of such digesters.

Table 7-1: Location, developer, Feedstock and power out of biogas digesters installed in South Africa (Mutungwazi et al., 2018, Franks et al., 2015)

Location	Developer	Feedstock	Power Output
Alice, Eastern cape	CAE / University of Fort Hare	4000 m^3 of dairy and piggery manure	2 × 132 kVa electricity generators
Athlone Industria	Alrode brewery Farm Secure Energy, Wastemart, CEA/New Horizon waste to energy	400 t of organic waste per day	
Bela-bela Limpopo Belville Bonnievale Bredasdorp Cavalter	CAE Humphries Boerdery piggery FarmSecure Carbon iBert iBert EnviroServ/ Chloorkop LFG Cullinan	Waste water treatment plant > 5 t bovine manure 4 t abattoir waste per day 20 t abattoir waste per day	100 kW 500 kW
Springs Stellenbosch	BiogasSA / Morgan Springs Abatrtoir Veolia water Technologies / Distell	Slaughter waste and organic waste 1000 m3 wastewater per day	0.4 MW
Table view KZN	Jeffares and Green / Bayside Mall Khanyisa projects	0.6–1 t of food waste per day Manure from 2+ cows, school	Rural cooking fuel

Location	Developer	Feedstock	Power Output
		organic and sewage waste	
Darling Uilenkraal Darling GrootPost Durban Durban	CAE/Uilenkraal dairy farm FarmSecure manure Bisasar road LFG Marrianhill LFG	Bovine manure Bovine manure 3500–5000 refuse per day 550–850 t per day	600 kW 6 MW 1.5 MW
Pretoria	Bio2watt / Bronkhorst-Spruit Biogas plant Prospection brewery	Manure	4.6 MW

The KwaZulu-Natal Province, has 26 operational digesters which are domiciled in the Illembe districts, and have a working volume of 6 m^3 (Munganga, 2013). The Limpopo Province has 55 digesters, installed mainly in the Mpfuneko region. (Altgen, 2016). Provinces such as Eastern Cape currently have a significant number of digesters (110 digesters) to be installed by the Melani Village Biogas Project. This is done in conjunction with the University of Fort Hare (Munganga, 2013). Other biogas installations include those instituted by developers such as BiogasPro Agama and BiogasSA wherein biogas digester were installed in areas such as schools, rural households, game farms etc. (Mutungwazi et al., 2018). In total, about 320 units have been installed in South Africa, predominantly in the Western Cape, and a few in the Eastern Cape and KwaZulu Natal Provinces. Considering the limited number of biogas installations in South Africa (Table 7-2), biogas technology in South Africa is still at infant stage compared to other countries such as Uganda and Kenya. The overview presented above suggests that limited research work has been done on the adoption of biogas technology in South Africa. The installation of small-scale biogas technology in rural communities thus presents an opportunity for a long term sustainable solution to the household energy issues in South Africa as a vast majority of the population living therein are poor (Agency, 2014).

Table 7-2: Number of digesters installed in selected African countries

Country	Year of Program Initiation	Cumulative Number of digesters installed up to 2015
Rwanda	2007	2619
Ethiopia	2008	5011
Tanzania	2008	4980
Kenya	2009	6749
Uganda	2009	3083
Burkina Faso	2009	2013
Cameroon	2009	159
Benin	2010	42
Senegal	2010	334
South Africa	2010	320

7.1.2 Biogas digester configurations

Numerous types of biogas plants over the world are available and their types are often determined by their mode of operation. Below is an overview of the various types of plants used in different countries.

A biogas plant typically has two components, namely a digester or fermentation tank and a gas holder. The digester component can be a waterproofed cube-shaped or cylindrical-shaped component. The digester component includes an inlet where the fermentable mixture can be fed into the digester in a slurry form.

Several forms of small to medium scale biogas technologies have been developed in African countries. These technologies include the floating drum, fixed dome and plastic bag design. The floating drum and the fixed dome have been used widely in Africa (Figure 7-2). These two technologies have the same digestion process (Amigun and Blottnitz, 2007), but the major difference between them is the method of gas collection. The fixed dome is equipped with a gas outlet where the gas is collected. It also has an overflow pipe to discharge the sludge into drainage. Below are descriptions as well as advantages and disadvantages of the two commonly used technologies.

The fixed dome

A fixed-dome plant consists of a digester with a fixed and non-movable gas holder located at the top of the digester (Figure 7-2), while the fixed volume structure is typically buried underground. The fixed dome digester was first developed in China (Kumar et al., 2015).

The slurry in the digester is forced into a separate tank by the increasing pressure of the biogas in the tank. The pressure in the digester thus enables the biogas flow through the pipeline, which can then be used for cooking, heating and if upgraded it can be used for electricity. The advantages and disadvantages of the fixed dome are presented in Table 7-3.

Table 7-3: Advantages and disadvantages of a fixed-dome plant (Bond and Templeton, 2011)

Advantages	**Disadvantages**
• Low initial costs and long useful lifespan	• Not easy to build, and thus, requires the supervision of experienced biogas technicians during construction
• Construction creates local employment	• The construction is labour intensive
• Underground construction saves space and protects the digester from temperature change	• Gas leaks could occur if not appropriately designed and constructed • Construction on bedrock could be difficult • Structural strength is required during construction

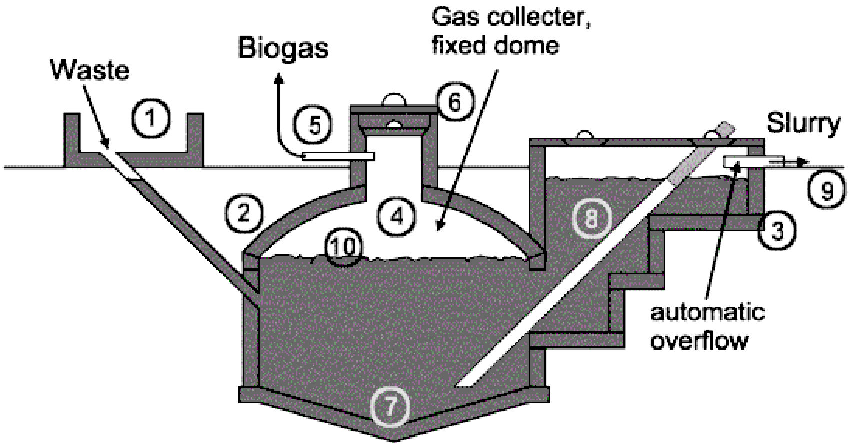


Figure 7-2: Fixed Dome (Energypedia, 2016)

The floating drum

A floating drum plant is often cylindrically-shaped or dome-shaped with the design originating from India (Mutungwazi et al., 2018). The floating drum plant consists of a gas holder that floats either directly into the fermenting slurry or into a separate water jacket. During operation, when the gas is produced, the drum moves upwards, and thereafter downwards, as soon as the gas is collected (Figure 7-3). The height of the drum is an indication of how much biogas has been produced. The floating drum digester has a constant pressure that is as a result of the weight of the drum relative to the cross-sectional area of the digester (Rajendran et al., 2012). The advantages and disadvantages of the floating drum configuration are outlined in Table 7-4.

Table 7-4: The advantages and disadvantages of a floating drum digester (Rajendran et al., 2012)

Advantages	**Disadvantages**
• It is easy to understand and operate	• Requires frequent coating with paint to avoid rust
• The gas produced has a constant pressure	• Fibrous materials may block the movement of the digester if not regularly maintained
• The gas storage is immediately visible	

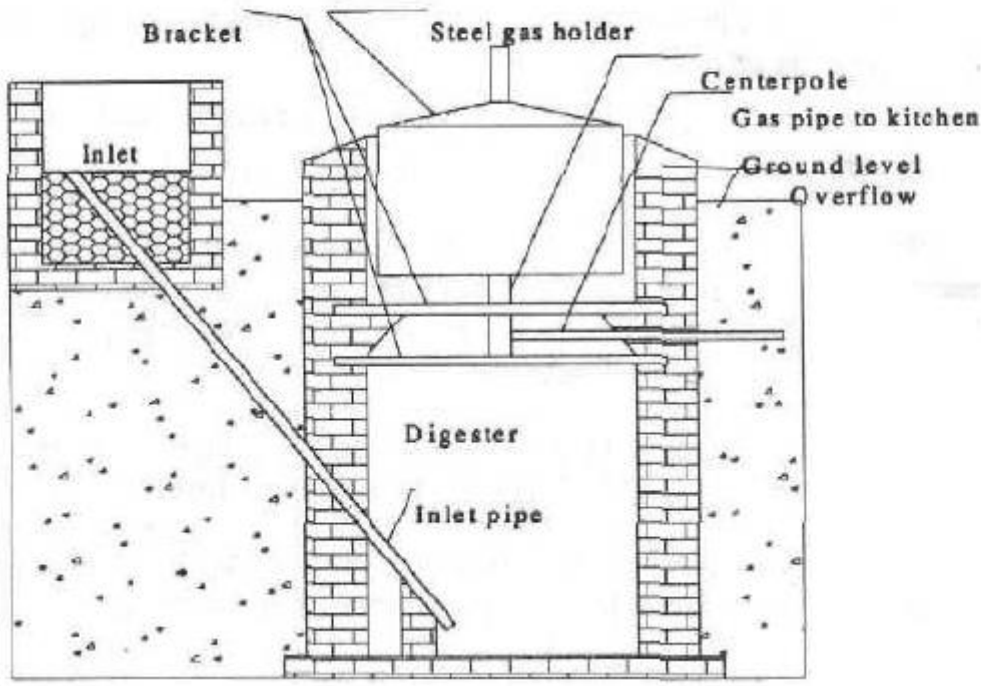


Figure 7-3: Floating Drum (Energypedia, 2016)

Flexible balloon digester

The flexible balloon digester consists of a long cylinder made from heavy duty PVC plastic that forms part of the anaerobic digester. Anaerobic digestion takes place in the cylinder and gas is stored as shown in Figure 7-4.

The feedstock inlet, slurry outlet and biogas outlet are attached to the wall of the digester. The flexibility of the digester is advantageous to the digestion process as it allows for some slight movement, which in turn agitates the feedstock. When the gas is at a maximum the balloon digester works like the fixed dome digester. The advantages and disadvantages of the system is outlined in Table 7-5.

Table 7-5: The advantages and disadvantages of the balloon digester (Balsam and Ryan, 2006)

Advantages	**Disadvantages**
• The construction process is much easier. Does not require high level skilled labour.	• The digester is constructed from heavy duty PVC pipes

Advantages	Disadvantages
	that might not be easily available in rural areas.
• The digester can be placed close to the use point, reducing the cost of gas piping.	• Reparation of a torn digester requires specialized plastic welding, which is unfavourable in rural setting.
• The digester is favourable in situations where there is a high water table and masonry or concrete cannot be used.	• Shorter life span of approximately 5 years.

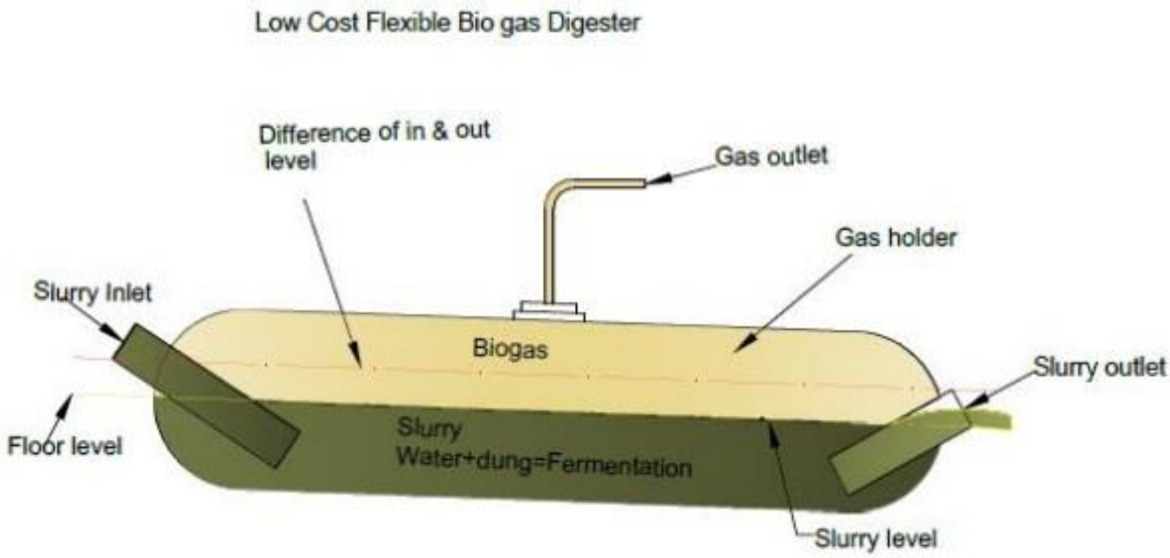


Figure 7-4: Balloon biogas digester (Florentino, 2003)

7.2 DESIGN OF DIGESTER

7.2.1 Experimental Data Analysis

With reference to chapter 6, at laboratory stage a 600ml capacity biogas digester with a working volume of 480ml giving a space head of 120ml for gas collection, was used to investigate the biogas yield of cassava co-digested with vegetable and fruit waste at different ratios.

The experimental data used for the pilot plant calculation is given from the results obtain the laboratory experiments conducted on the co-digestion of cassava biomass (CB) and vegetable & fruit waste (VF) as presented in chapter 6. The maximum cumulative biogas yield (1641.82 ml/g) was obtained from the co-digestion ratio of 40:60 (CB:VF) inoculated with cattle dung.

7.2.2 Digester Design Calculations

The size of the biogas digester depends on the desired volume of the biogas required daily yield. The volume of the gas holder should be equal to one (1) day's biogas yield. As discussed in section 7.1.1, various digester designs are available, however, the fixed dome design is adopted in this study as it contains key advantages which includes cost as it is relatively cheap and durable, all the parts are fixed with no moving parts and well insulated since it is constructed below ground level (Nijaguna, 2006, Omer and Fadalla, 2003). This study thus presents the design of a flat-bottomed fixed dome digester for biogas generation from the co-digestion of cassava biomass, vegetable and fruit waste.

The digester is designed to produce gas that would serve a family of five (5) with an assumption that each family has eight (8) people. Therefore, the requirements and criteria adopted in implementation the design are as follow:

According to Mital (1996), the amount of gas required for cooking per person/day is 0.25 m^3/ person/day. Therefore the biogas digester is design mathematically to produce 10 m^3/day of biogas (Kaur and Kumar, 2017). The following steps were followed in the sizing of the biogas digester (Nijaguna, 2006):

A) Gas Production Rate (G)
B) Active Slurry Volume (Vs)
C) Dimension Calculation (H & D)
D) Slurry displacement inside digester (d)
E) Slurry displacement in the inlet and outlet chamber (h)
F) Length (l) and breadth (b) of the inlet and outlet chambers
G) Dome height (d_h) calculation
H) Radius of the dome (r)

For the co-digestion of cassava biomass (unpeeled) and vegetable & fruits with a ratio of 40:60 (CB : VF).

$$57.05\ g = 0.0570\ kg = \frac{37995.03\ kg}{31\ days} = 1.225\ l/day$$

$$1\ kg\ produced = \frac{1.225}{0.05705} x\ 1 = 21.48\ l/day$$

$$21.48\ l/day = 0.02148\ m^3/day$$

A) ***<u>Gas Production Rate (G)</u>***

$$G = W\ x\ 0.0215 \tag{7-1}$$

W = weight of biomass

G = gas Production rate

The biogas digester is designed for G = 10 m^3/day so this value is put into Equation 7-1.

$$10 = W\ x\ 0.0215$$

$$W = \frac{0.0215}{10} = 465.12\ kg$$

On solving equation 7-1 we get W = 465.12 kg/day

B) ***<u>Active Slurry Volume (Vs)</u>***

The volume of the digester which will be filled with undigested feedstock (Biomass + Water). The volume of the active slurry volume (Vs) is calculated by Equation 7-2.

$$V_s = HRT\ x\ \frac{2W}{1000} \tag{7-2}$$

$$V_s = 31\ x\ \frac{2\ x\ 465.12}{1000} = 28.84\ m^3$$

Where:

W = Weight of Biomass (465.12 kg)

HRT = Hydraulic Retention Time (31 days)

C) ***Dimension Calculation (Height & Diameter)***

The biogas digester uses the ratio of height and diameter, these ratio are usually set to be D : 2H. The digester shape selected is cylinder therefore the volume of the cylinder is found by Equation 7-3.

$$V_s = \frac{\pi}{4}\ x\ H\ x\ D^2 \tag{7-3}$$

$$V_s = \frac{\pi}{4}\ x\ H\ x\ (2H)^2$$

$$V_s = \frac{\pi}{4}\ x\ H\ x\ 4H^2$$

$$H = \left(\frac{V_s}{\pi}\right)^{\frac{1}{3}} \tag{7-4}$$

$$H = \left(\frac{28.84}{3.14}\right)^{\frac{1}{3}} = 2.09\ m$$

$$D = 2H = 2\ x\ 2.09 = 4.19\ m$$

Where:

V_s = Volume of active slurry

H = Digester height

D = Digester Diameter

D) ***Slurry displacement inside digester (d)***

Assuming the cooking is done two (2) time a day namely afternoon and evening. Assuming that 50% of the gas produced in a day is available for one (1) cooking with each cooking span of 3 hours. The slurry displacement depends on the gas storage volume V_{sd} which is achieved by Equation 7-5.

$$\left(\frac{C_o}{24}\right) x\ G + V_{sd} = 0.5G \tag{7-5}$$

$$\left(\frac{3}{24}\right) x\ G + V_{sd} = 0.5G$$

$$V_{sd} = 0.5G - \frac{3}{24}G = 0.375G \approx 0.4G$$

$$d = \frac{\pi}{4}\ x\ D^2 d = V_{sd} = 0.4G \qquad (7\text{-}6)$$

$$V_s = HRT\ x \frac{2W}{1000}$$

$$V_s = 31\ x \frac{2\ x\ G}{1000}\ x \frac{1}{0.012}$$

$$V_s = 2.884G$$

$$V_{sd} = \frac{\pi}{4}\ x\ D^2 d$$

$$\frac{\pi}{4}\ x\ D^2 d = \frac{\pi}{4}\ x\ D^2\ x \frac{H}{2.884}\ x\ G = 0.4G$$

$$d = \frac{H}{2.884}\ x\ 0.4 = \frac{2.09}{2.88}\ x\ 0.4 = 0.29\ m$$

Where:

C_o = cooking time

G = Gas Production Rate

d = slurry displacement insider digester

D = Gas Production Rate

V_{sd} = Gas storage volume

E) Slurry displacement in the inlet and outlet chamber (h)

Pressure is selected to be 0.85m water gauge as a safe limit for brick or concrete dome (Nijaguna, 2006). Therefore, the slurry displacement height in the inlet and outlet is obtained using Equation 7-7 below:

$h + d = 0.85$ (7-7)

$h = 0.85 - 0.29 = 0.56\ m$

Where:

h = slurry displacement in the inlet and outlet chamber

d = slurry displacement inside digester

F) ***Length (l) and breadth (b) of the inlet and outlet chambers***

The length and breadth of the inlet and outlet chamber is obtained using equation 8, taking that the length (l) = 1.5 breadth (b). The inlet and outlet are assumed to be identical.

$2\ x\ l\ x\ b\ x\ h = V_{sd} = 0.4G$ (7-8)

$l = 1.5b$

$$b = \left(\frac{0.2G}{1.5h}\right)^{\frac{1}{2}}$$

$$b = \left(\frac{0.2\ x\ 10}{1.5\ x\ 0.56}\right)^{\frac{1}{2}} = 1.54m$$

$l = 1.5\ x\ 1.54 = 2.31m$

Where:

l = length of chamber

b = Breadth of inlet and outlet chamber

h = height of inlet and outlet chamber

G) ***Dome height (d_h) calculation***

The volume of the dome that is spherical in shape is given by Equation 7-9:

$$V_d = \frac{\pi}{6}\ x\ d_h\ x \left[3\ x\ \left(\frac{D}{2}\right)^2 + d_h^2\right] \tag{7-9}$$

$$V_{sd} = 0.4G$$

$$V_d = G - 0.4G = 0.6G$$

$$p = 0.75D^2 = 0.75\ x\ 4.19^2 = 13.17\ m$$

$$q = -0.6\ x\ \left(\frac{6}{\pi}\right) G = -0.6\ x \left(\frac{6}{\pi}\right)\ x\ 10 = -11.5m$$

$$R = \left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2 = \left(\frac{13.17}{3}\right)^3 + \left(\frac{11.5}{2}\right)^2 = 117.66\ m$$

$$A = \left[\left(\frac{-q}{2}\right) + \sqrt{R}\right]^{\frac{1}{3}} = \left[\left(\frac{11.5}{2}\right) + \sqrt{117.66}\right]^{\frac{1}{3}} = 2.55\ m$$

$$B = \left[\left(\frac{-q}{2}\right) - \sqrt{R}\right]^{\frac{1}{3}} = \left[\left(\frac{11.5}{2}\right) - \sqrt{117.66}\right]^{\frac{1}{3}} = -1.72\ m$$

$$d_h = A + B = 2.55 - 1.72 = 0.829m$$

Where:

d = slurry displacement insider digester

D = Gas Production Rate

V_{sd} = Gas storage volume

*H) **Radius of the dome (r)***

The radius of the dome is obtained using Equation 7-10:

$$r = \frac{\left(\frac{D}{2}\right)^2 + d_h^2}{2d_h} = 3.06\ m \tag{7-10}$$

Table 7-6 below presents the design parameters used in sizing of the digester and also indicating the critical dimension of the digester for the purpose of construction with the drawing presented in Appendix D1.

For the inlet and outlet, (i.e. opening boxes), a dimension of 0.6 m x 0.6 m was used to allow for entry and exit of construction and maintenance personnel into the digester when necessary.

7.2.3 Agitator/impeller Design Calculations

At the laboratory stage, two layers were observed in the digester bottle after some period, depicting a separation between the biomass and water. This could be a disadvantage as the gas gets trapped in the layers of the biomass. The trapped gas only be released by shaking the bottle. To prevent trapping of the gas and ensure proper gas transfer, an agitator was designed using the steps below (Appendix D1);

A) Calculation of diameter of three blade type agitator (D_a)
B) Calculation of height of impeller (H_a)

A) <u>Calculation of diameter of three blade type agitator (D_a)</u>

The diameter of the impeller is determined using the total height of digester and diameter of the digester using the Equation 7-11 (Low, 2014) below:

$$\frac{D_a}{D} = \frac{1}{3} \qquad (7\text{-}11)$$

$$D_a = \frac{1}{3}\ x\ D$$

$$D_a = \frac{1}{3}\ x\ 4.19 = 1.40\ m$$

Where:

$D_a = diameter\ of\ impeller$

$D = diamter\ of\ digester$

B) <u>Calculation of total height of impeller (H_P)</u>

The total height of the impeller is determined using the relationship of the height of impeller in cylinder added to the height of the dome (Equation 7-12).

$$H_p = H_{pa} + dh \quad (7\text{-}12)$$

$$\frac{H_p}{D_a} = \frac{1}{1}$$

$$H_p = \frac{1}{1} x\, D_a$$

$$H_p = \frac{1}{1}\ x\ 1.40 =$$

Where:

$H_p = Total\ height\ of\ impeller$

$H_{pa} = Height\ of\ impeller\ in\ cylinder$

$dh = height\ of\ dome$

7.2.4 Material Estimation for the Plant

Material estimate for the plant is required to have the correct cost estimate for construction purpose and to avoid wastage of material and finance. The material estimate is divided into three (3) category listed below:

A) Concrete: the calculation of all concrete required including the following, concrete for bottom of digester, concrete for inlet and outlet box, concrete slab to cover inlet and outlet chamber, concrete for lentils,

B) Brickwork

A) <u>Concrete</u>

Concrete at bottom of digester

$$At\ the\ bottom\ of\ digester = \frac{\pi}{4}\ x\ [D + 2\ (digester\ wall\ thickness) + 0.2]^2 x\ 0.1 \quad (7\text{-}13)$$

$Thickness\ of\ digester\ wall\ =\ 0.23m$

$D\ =\ 4.13m$

$$Volume\ of\ concrete\ required\ for\ bottom\ = \frac{\pi}{4}\ x\ [4.13\ x\ (2\ x\ 0.23) + 0.2]^2 x\ 0.1$$

$$= 1.80\ m^3$$

Concreting at the inlet and outlet

$Inlet\ box\ taken\ as\ rectangular\ box\ with\ 0.75\ m\ x\ 1.00\ m.$

$Outlet\ box\ taken\ to\ be\ square\ box\ with\ 1.05\ x\ 1.00\ m$

$Volume\ of\ concrete\ required\ =\ (0.75\ x\ 1.00\ x\ 0.1)\ +\ (1.05\ x\ 1.00\ x\ 0.1)\ =\ 0.18\ m^3$

Concrete for inlet and outlet chamber

$$Based\ on\ the\ shape\ of\ the\ inlet\ and\ outlet\ dimensions\ =\ (l\ +\ 0.46\ +\ 0.2)\ x\ (b\ +\ 0.46\ +\ 0.2) \quad (7\text{-}14)$$

$$Volume\ of\ concrete\ required\ =\ 2\ x\ (l\ +\ 0.46\ +\ 0.2)\ x\ (b\ +\ 0.46\ +\ 0.2)\ x\ 0.1$$

$$=\ 2\ x\ (2.31\ +\ 0.46\ +\ 0.2)\ x\ (1.54\ +\ 0.46\ +\ 0.2)\ x\ 0.1$$

$$=1.31\ m^3$$

$$Volume\ of\ concrete\ to\ be\ substrated\ as\ inlet\ and\ outlet\ chamber\ not\ completely\ concrete\ =\ -[(0.6\ x\ 0.6\ x\ 0.1)\ +\ (b\ x\ 0.6\ x\ 0.1)]$$

$$=\ -[(0.6\ x\ 0.6\ x\ 0.1)\ +\ (1.54\ x\ 0.6\ x\ 0.1)]$$

$$=\ -0.13\ m^3$$

$$Volume\ of\ concrete\ required\ =\ 1.13 - 0.13$$

$$=\ 1.18\ m^3$$

Volume of the concrete lentils

$Volume\ of\ concrete\ required\ for\ lentils\ =\ 2\ x\ 0.9\ x\ 0.23\ x\ 0.1\ =\ 0.04\ m^3$

Volume of concrete slab for chambers (VCSC)

$$VCSC\ =\ 2\ x\ (l\ +\ 0.46)\ x\ (b\ +\ 0.46)\ x\ 0.075 \quad (7\text{-}15)$$

$$=\ 2\ x\ (2.31\ +\ 0.46)\ x\ (1.54\ +\ 0.46)\ x\ 0.075\ =\ 0.831 m^3$$

The total volume of concrete required was obtained by adding all concrete quantities which sums up to 4.031m^3 (Table 7-7). In the construction of the fixed dome digester the reinforced cement concrete mixed proportion of 1:2:4 (cement: sand: aggregate stone) will be used (Adewole et al., 2015).

The material required for 1 m^3 of concrete is:

$Cement: 0.22\ m^3\ (6.6\ bags);\ for\ 4.031\ m^3\ of\ concrete\ 0.887\ m^3 (26.6\ bags)$

$of\ cement\ is\ needed.$

$Sand: 0.44\ m^3;\ for\ 4.031\ m^3\ of\ concrete\ 1.77\ m^3\ of\ sand\ is\ needed.$

$Aggregate\ (25\ mm): 0.88\ m^3;\ for\ 4.031\ m^3\ of\ concrete\ 3.55\ m^3\ of\ stone\ is\ needed.$

$Steel\ (8mm): 40\ kg;\ for\ 4.031\ m^3\ of\ concrete\ 161.24\ kg\ of\ steel\ is\ needed$

$Binding\ wire: 0.10\ kg;\ for\ 4.031\ m^3\ of\ concrete\ 0.403\ kg\ of\ wire\ is\ needed.$

B) Brickwork

Digester wall

$$Volume\ of\ brickwork\ needed\ = \left(\frac{\pi}{4}\right) x\ [(D\ +\ 0.46)^2 - D^2]\ x\ (H\ +\ D) \tag{7-16}$$

$$= \left(\frac{\pi}{4}\right) x\ [(4.19\ +\ 0.46)^2 - 4.19^2] x\ (2.09\ +\ 4.19) = 20.06\ m^3$$

$$Openings\ for\ inlet/outlet\ =\ 2\ x\ (0.6\ x\ 0.23\ x\ 0.6)\ =\ 0.17\ m^3$$

$$Lintels\ =\ 2\ x\ (0.9\ x\ 0.23\ x\ 0.1)\ =\ 0.04\ m^3$$

$$Total\ volume\ of\ brickwork\ required\ for\ digester\ wall\ =\ 20.06 - 0.17 - 0.04$$
$$=\ 19.85\ m^3$$

Materials needed for 1 m^3 for the digester wall

$Bricks\ (0.23m\ x\ 0.115m\ x\ 0.075m) :\ 500\ numbers;\ for\ 19.85\ m^3\ =\ 9925\ bricks$

$Cement: 0.05\ m3\ (1.5\ bags)\ ;\ for\ 19.85\ m^3\ =\ 0.9925\ m^3\ (29.77\ bags)$

$Aggregate\ stone: 0.25\ m^3;\ for\ 19.85\ m3\ =\ 4.96\ m^3$

Inlet/Outlet chamber

$Volume\ of\ brickwork\ needed\ for\ inlet/outlet\ chambers\ =\ 4\ x\ (l\ +\ b\ +\ 0.46)\ x\ 0.23\ x\ (h\ +\ 0.15)$ (7-17)

$$=\ 4\ x\ (2.31\ +\ 1.54\ +\ 0.46) x\ 0.23\ x\ (0.56 +\ 0.15) = 2.82m^3$$

Materials needed for 1 m³ for inlet/outlet chamber

$Bricks\ (0.23m\ x\ 0.115m\ x\ 0.075m)\ :\ 500\ numbers;\ for\ 2.82\ m^3\ =\ 1408\ bricks$

$Cement: 0.05\ m3\ (1.5\ bags)\ ;\ for\ 2.82\ m^3\ =\ 0.141\ m^3\ (4.23\ bags)$

$Aggregate\ stone: 0.25\ m3\ ;\ for\ 2.82\ m^3 =\ 0.705\ m^3$

Inlet/outlet boxes

$Inlet\ box\ side\ walls\ =\ 2\ x\ \frac{0.4 + (b\ +\ 0.1)}{2}\ x\ (0.6\ +\ d - 0.1)$ (7-18)

$$Inlet\ box\ side\ walls\ =\ 2\ x\ \frac{0.4 +\ (1.54 +\ 0.1)}{2}\ x\ (0.6\ +\ 0.29 - \ 0.1) = 1.61m^2$$

$inlet\ box\ sloping\ wall\ =\ [(b - \ 0.3)^2\ +\ (0.6\ +\ d - \ 0.1)^2]^{\frac{1}{2}}\ x\ 0.6$ (7-19)

$$= [(1.54 - 0.3)^2 + (0.6 + 0.29 - 0.1)^2]^{\frac{1}{2}}\ x\ 0.6 = 0.882m^2$$

$Outlet\ box\ =\ 2\ x\ 0.7\ x\ (0.6 + d - 0.1)$ (7-20)

$$= 2\ x\ 0.7\ x\ (0.6\ +\ 0.29 - \ 0.1) = 1.106m^2$$

$Side\ walls\ of\ inlet/outlet\ =\ 1\ x\ 0.6\ x\ (0.6\ +\ d - \ 0.1)$ (7-21)

$$=\ 1\ x\ 0.6\ x\ (0.6\ +\ 0.29 - \ 0.1) = 0.474m^2$$

$Total\ area\ =\ 1.61 + 0.882 + 1.106 +\ 0.474 = 4.072m^2$

The material required for 10m² area:

$Bricks: 500\ numbers$

$Cement: 0.05\ m3\ (1.5\ bags)$

$Sand\ (coarse): 0.25\ m^3$

Therefore for area of 4.072 m^2 the material required are:

$Bricks$: 203.6 $numbers$

$Cement$: 0.0204 m^3 (0.6 $bags$)

$Sand$ ($coarse$): 0.102 m^3

Bricks for the construction of dome

The construction of the dome will be done using the first-class brick bonded with CM 1:2

$$Area\ of\ the\ dome\ =\ 2\ x\ \pi\ x\ (r + 0.05)\ x\ (d_h + 0.05) \quad (7\text{-}22)$$

$$=\ 2\ x\ \pi\ x\ (3.06\ + 0.05)\ x\ (0.829\ + 0.05) = 17.18m^2$$

$$One\ brick\ layer\ around\ the\ dome\ as\ a\ first\ ring = \pi\ x\ D\ x\ 0.1 \quad (7\text{-}23)$$

$$= \pi\ x\ 4.19\ x\ 0.1 = 1.316m^2$$

$$Total\ area\ of\ Dome\ =\ 17.18\ +\ 1.316\ =\ 18.496m^2$$

The material required for 10m^2 area:

$Bricks$: 370 $numbers$

$Cement$: 0.05 m^3 (1.5 $bags$)

$Sand$ ($coarse$): 0.11 m^3

Therefore, for area of 18.49 m^2 the material required are:

$Bricks$: 685 $numbers$

$Cement$: 0.0925 m^3 (2.8 $bags$)

$Sand$ ($coarse$): 0.203 m^3

Brick tiles for the digester dome

The digester dome will be covered with brick tiles and the number of times required is calculated below:

$$Total\ area\ of\ brick\ tile\ =\ 2\ x\ \pi\ x\ (r + 0.17)\ x\ (d_h + 0.17) \qquad (7\text{-}24)$$

$$=\ 2\ x\ \pi\ x\ (3.06 + 0.17)\ x\ (0.829 + 0.17) = 20.27m^2$$

The material required for 10m^2 area:

$Bricks$: 370 $numbers$

$Cement$: 0.1 m^3 (3.0 $bags$)

$Sand\ (coarse)$: 0.04 m^3

Therefore, for area of 20.27 m^2 the material required are:

$Bricks$: 750 $numbers$

$Cement$: 0.203 m^3 (6.08 $bags$)

$Sand\ (coarse)$: 0.081 m^3

7.2.5 Cost estimate to construct

A cost estimate to construct the biogas digester was calculated based on material only no labour, transportation and all other construction obligations was included.

7.3 RESULTS AND DISCUSSION

To construct a biogas digester plant for a family of five (5) with each family having eight (8) people. An underground fixed dome is used having a spherical dome, the underground was selected as to preserve the heat of 37 °C. The gas production rate of the co-digestion slurry of cassava biomass and vegetable and fruit waste was 0.02148 m^3/day, however, the digester is required to produce a gas at 10 m^3/day therefore a feed of 465.12 kg/day is required. Table 7-6 presents a summary of the digester dimension for construction purposes.

Table 7-6: Design parameter for fixed dome digester

Parameters	**Values**
Gas Production Rate (G)	10 m^3/day

Parameters	Values
Active Slurry Volume (Vs)	28.84 m^3
Height of Cylindrical Digester (H)	2.09 m
Diameter of Digester (D)	4.19 m
Slurry Displacement (d)	0.29 m
Height of Slurry displacement (h)	0.56 m
Breadth of inlet and outlet (b)	1.54 m
Length of inlet and outlet (l)	2.31 m
Dome height (d_h)	0.829 m
Radius of Dome (r)	3.06 m

The total volume of concrete required for the construction of the anaerobic digester is obtained by summing up all the quantities of concrete which is presented in Table 7-7.

Table 7-7: Total volume of concrete for energy requirement of 0.25 m^3/person/day

Concrete Item	Volume
Bottom of digester	1.80 m^3
Inlet and outlet	0.18 m^3
Inlet and outlet chamber	1.18 m^3
Lentils	0.04 m^3
Slab for chambers	0.831m^3
Total	**4.031m^3**

A cost estimate to construct the biogas digester was calculated based on material only no labour, transportation and all other construction obligations was included. Table 7-8 presents the cost estimate.

Table 7-8: Cost estimate to construct biogas digester for 0.25 m^3/person/day

Items	Units	Quantities	Rate	Amount
Concrete	no	4.031	R 950.00	R 3 829.45
Bricks	kg	13000	R 5.69	R 73 970.00
Binding Wire	tonnes	0.5	R 250.00	R 125.00
Stone Ballast (25 mm)	m^3	3.55	R 750.00	R 7 721.25
Sand (Fine)	m^3	2.2	R 350.00	R 770.00
Chicken Wire Mesh	kg	27	R 725.00	R 19 575.00
Steel (8mm)	m	161.24	R 45.94	R 7 407.37
Steel rings around the base of the dome	m	29.47	R 15.34	R 452.07
GI pipe for outlet	bags	0.45	R 35.00	R 15.75
Cement	no	84	R 86.55	R 7 270.20
Total				**R 121 136.09**

7.4 CONCLUSION

As the demand for energy increases, the demand for alternative renewable energy such as biogas increases. Considering that the installation of biogas plants in South Africa is still in an infant stage, more installations are required. This study provides a platform for understanding the process of sizing of digesters using a family in a rural area in a scenario analysis. A full-scale anaerobic digester was designed to produce biogas from cassava, vegetable and fruit waste. The material required to construct the digester was calculated. The fixed dome digester was designed as a batch digester to produce 10m^3 of gas for a family of five (5) given that each family has eight (8) people. The digester consisted of inlet and outlet chamber, volume of the fermentation chamber and a gas storage chamber. The digester diameter for the required gas production rate is 4.19m with a digester height of 2.09m at a material cost of R 121

136.09. Further research on the economic feasibility of the project and construction cost is recommended. Moreover, the methods of purification of biogas and biogas storage requires further research.

CHAPTER 8:
CONCLUSIONS AND RECOMMENDATIONS

PREFACE

This chapter presents a summary of the key findings and conclusions of the study as well as recommendations for future works. This chapter also elucidates the various contributions to knowledge generated from this study.

8.1 BACKGROUND AND RATIONALE

The decline in electricity reserve margin resulted in blackouts in 2008 that affected the economic sector of the South Africa. Demand and supply was managed through a process of load shedding to improve the energy situation (Odhiambo, 2009). During this process, electricity generation is aligned with the demand and at the same time a reasonable electricity reserve margin is maintained. The financial impact of load shedding during the period November 2007—January 2008 amounted to ZAR 50 billion (USD 6.6 billion). However, the overall costs are much greater. A 4% drop in the economic growth resulted in 2008. South Africa depends mainly on coal, 84% of energy generation was from fossil fuels, of which 72% came from coal and 12.4% from oil. The production of electricity from coal is amongst the cheapest electricity in the world (Amigun et al., 2011). However, South African coal has high ash content that varies from 5% to 15%, which results in particulate and gases that have a negative effect on the quality of the air in the surrounding areas. The gases emitted also contribute to global warming. South Africa needs more energy to sustain its economy and to maintain to the standards of an emerging country that can reach the level of developed world in the future. According to Pegels (2010), South Africa has high potential for renewable energy generation. Various studies support this view. However, there is still lacking initiative and will in Africa, particularly South Africa to transform the research into a product for consumers at a commercial scale (South Africa National Energy Association, 2010).

In South Africa, most renewable energy is derived from biomass (Musango *et al*., 2011). About 18 million tonnes of agricultural and forestry residue is produced in South Africa per annum (Lynd *et al*., 2003). South Africa has the potential to produce about

67 million tonnes of energy crops on 10% of the available land (Marrison and Larson, 1996). Biomass already contributes between 9 and 14% of the total energy requirement, but it could be utilized more efficiently, and the current use is not always sustainable. The key issues faced by many developed and developing countries of the world today are mainly future energy security and better use of natural resources. About 70% of the countries in Africa rely on imported energy. The focus of the study was to investigate the suitability of cassava as an alternative source of biomass feedstock for biogas production in South Africa, through co-digestion with other available biomass, thereby designing a digester for local communities.

8.2 MAJOR FINDINGS AND CONCLUSIONS OF THE STUDY

Cassava has a great potential for bioenergy production with greater advantages towards biogas, in particular. South Africa has thousands of acres of lands that are degraded and unutilized since the lands have been degraded. Cassava provides advantages over other crops because it can thrive in these kinds of lands as it thrives well on soils of relatively low fertility where the use of the lands would be uneconomical (Rodrigues et al., 2018). According to Popp et al. (2014), cassava can be produced on degraded lands making it have an additional advantage that it can be produced in large scale for biofuels without posing a risk to food production and or its natural habitats. The above advantages of cassava motivated this research as there has been scarce literature that addresses the co-digestion of cassava and vegetable & fruits waste especially in South Africa. Most research have focused on cassava peels (Ezekoye, 2008, Adelekan and Bamgboye, 2009, Oparaku et al., 2013), and the peeled cassava solely digested (mono-digestion). No much research has been conducted on co-digestion of cassava with vegetables & fruits waste. Findings from this study thus display various areas wherein original contribution to knowledge has been made. The study also presents how the research findings can be implemented practically through a design of biogas digester for a community. The study produced a series of interesting results that are summarized as follows:

The overall objective of Chapter 3 entitled ***“Identification and Characterization of Potential Feedstock for Biogas Production in South Africa”*** was to investigate the different feedstock with the potential to produce biogas. This was done through characterization of different feedstock, and additionally, through preliminary calculation of the theoretical biogas and methane yield of the identified feedstock. The theoretical yield calculation was based on the physical-chemical characterization. The results revealed that cassava, vegetables and fruits have the necessary characteristics to produce biogas. Co-digestion analysis based on elemental analysis demonstrated that optimal co-digestion ratios to improve the biogas yield. These promising results encouraged the authors to conduct BMP to investigate the biogas yield at laboratory scale using a 600 ml reactor to compare the theoretical yield. This was addressed in chapter 4.

Chapter 4 entitled ***"Co-Digestion of Animal Manure and Cassava Peel for Biogas Production in South Africa"*** aimed to determine the performance of co-digestion of cassava peel at different inoculate ratios of cattle manure. The results showed that co-digestion influenced biogas production and methane yield. The final cumulative methane yields by the co-digestion of CM and CP at the CM:CP mixing ratios of 80:20 and 20:80 were 738.76 mL and 838.70 mL respectively. The corresponding average daily methane yields were 18.42 mL/day and 20.97 mL/day. This study thus suggests that methane production could be enhanced using CP in a co-digestion process and at a 20:80 CM:CP ratio being the promising ratio which yielded the highest amount of biogas. The analysis of variance amongst the biogas yields indicate that different co-digestion mixtures have an important effect on the ultimate yields. With the promising performance of cassava peel, further investigations and modelling into the performance of peeled cassava compared to unpeeled cassava was thus conducted in Chapter 5.

Chapter 5 entitled ***"Comparison and Modelling of Biogas Production from Unpeeled and Peeled Cassava Tubers at a Mesophilic Temperature"*** is a pilot study focused on the production of biogas from cassava in South Africa. It is expected that this study will contribute towards establishing an accurate technique for biogas quantification using UCT and PCT, and contribute to knowledge on the suitable feedstock that can provide an optimum biogas yield. The influence/effect of the cassava peels on the biogas yield was also assessed. The results showed that anaerobic digestion of peeled cassava tuber in the presence of inoculum (PCT^1) yields the most viable results, thereby suggesting that the use of unpeeled cassava tuber slows down the digestion process thereby reducing the biogas yield. These results are in agreement with that obtained by Budiyono et al. (2013) which submits that the inoculation of feedstock with fresh manure can increase the biogas yield by 30%. Furthermore, mechanical pre-treatment of the substrate by removing the cassava peel is highly recommended to ensure high conversion rates. A reduction in biogas yield was observed for the peeled fraction and this can be attributed to its slow degradability (Jekayinfa and Scholz, 2013). Due to low amounts cassava farming in South Africa, the potential of energy production of mono-digestion of cassava biomass for the biogas process would be rather low, therefore the need to explore co-digestion with available waste stream such as vegetable and fruit (VF) waste was explored, with results indicating the potential of VF to produce biogas. Further investigations and optimization of co-digestion of cassava with vegetable and fruit waste were conducted in chapter 6.

Chapter 6 entitled "***Optimization of Biogas Yield through Co-Digestion of Cassava Biomass and Vegetable & Fruits Waste at Mesophilic Temperatures"*** focuses on the optimum biogas yield through co-digestion of cassava biomass, vegetable and fruits at different ratios in a single stage fed-batch anaerobic digester for biogas production. Following this investigation coupled with modelling of the biogas yield of cassava biomass, vegetable and fruits waste, the results affirmed the conclusion reached in chapter 3 that co-digestion of cassava biomass, vegetable and fruit waste enhances the biogas yield. It was observed that under anaerobic conditions in the presence of inoculum, co-digestion 40:60 (CB;VF) achieved the maximum methane yield which was 23.08% greater than that of mono-digestion. It is worthy to note that an increase in the cassava biomass above 40% in relation to the vegetable and fruit waste had a negative effect on the yield. The omission of inoculum in the best performing co-digestion (40:60) affected the biogas yield as it reduced significantly. Notwithstanding, the performance exhibited by the co-digestion ratio of 40%CB:60%VF was satisfactory as it performed better than that of cassava biomass digestion on its own. Using the results obtained in chapter 6, further investigation was conducted by upscaling the results to design a pilot digester which is presented in chapter 7.

The design of an anaerobic digester for sustainable co-digestion of cassava, vegetable and fruit waste was covered under the Chapter 7 entitled ***"Biogas Technology and***

the Design of Pilot Digester for Co-Digestion of Cassava and Vegetable & Fruits Waste". The digester was designed to produce biogas energy that will cater for five (5) families; each comprising eight (8) members. The energy requirement for cooking purposes was estimated to be 0.25 m^3/person/day, while the biogas production rate of the digester was estimated to be 10 m^3/day. The digester was designed as a fixed dome digester which consisted of fermentation chamber and gas storage chamber. The dimensions of the digester were height of cylindrical digester (H) 2.09 m, diameter of digester (D) 4.19 m, breadth of inlet and outlet (b) 1.54 m, dome height (d_h) 0.829 m and radius of dome (r) 3.06 m.

8.3 FUTURE WORK/RESEARCH

This research was successfully conducted and the bio-digester design, however based on the finding of this study, the following recommended research have emanated and can be undertaken in future studies:

1) The construction of a large-scale bio-digester based on the design put forward in this study of the digester.
2) The modelling of the anaerobic digestion process using artificial intelligence techniques with focus on batch system.
3) The use of cassava as a landfill cap as it thrives well on soils of relatively low fertility making it advantageous in land where cultivation of other crops is uneconomical.

REFERENCES

Abubakar, B. & Ismail, N. 2012. Anaerobic digestion of cow dung for biogas production. *ARPN journal of engineering and applied sciences,* 7**,** 169-172.

Achinas, S., Achinas, V. & Euverink, G. J. W. 2017. A technological overview of biogas production from biowaste. *Engineering,* 3**,** 299-307.

Adelekan, B. & Bamgboye, A. 2009. Comparison of biogas productivity of cassava peels mixed in selected ratios with major livestock waste types. *African Journal of Agricultural Research,* 4**,** 571-577.

Adewole, K. K., Ajagbe, W. O. & Arasi, I. A. 2015. Determination of appropriate mix ratios for concrete grades using Nigerian Portland-limestone grades 32.5 and 42.5. *Leonardo Electronic Journal of Practices and Technologies,* 26**,** 79-88.

Agency, I. E. 2014. Africa energy outlook: A focus on energy prospects in Sub-Saharan Africa. International Energy Agency Paris, France.

Ai, B., Li, J., Chi, X., Meng, J., Jha, A. K., Liu, C. & Shi, E. 2014. Effect of pH and buffer on butyric acid production and microbial community characteristics in bioconversion of rice straw with undefined mixed culture. *Biotechnology and bioprocess engineering,* 19**,** 676-686.

Akinyemi, S., Akinlua, A., Petrik, L. & Gitari, W. 2012. *Mineralogy and geochemistry of sub-bituminous coal and its combustion products from Mpumalanga Province*, INTECH Open Access Publisher. South Africa

Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. & Janssen, R. 2008. Biogas Handbook.–University of Southern Denmark Esbjerg. ISBN 978-87-992962-0-0.

Alakangas, E. 2015. Quality guidelines for wood fuels in Finland. *VTT Technical Research Centre of Finland*.

Ali Shah, F., Mahmood, Q., Maroof Shah, M., Pervez, A. & Ahmad Asad, S. 2014. Microbial ecology of anaerobic digesters: the key players of anaerobiosis. *The Scientific World Journal,* 2014.

Altgen 2016. Biogas industry in South Africa an assessment of the skills need and estimation of the job potential. South Africa.

Amigun, B. & Blottnitz, H. V. 2007. Investigation of scale economies for African biogas installations. *Energy Conversion and Management,* 48**,** 3090-3094.

Amigun, B., Musango, J. & Brent, A. 2011. Community perspectives on the introduction of biodiesel production in the Eastern Cape Province of South Africa. *Energy,* 36**,** 2502-2508.

Amigun, B., Parawira, W., Musango, J., Aboyade, A. & Badmos, A. 2012. Anaerobic biogas generation for rural area energy provision in Africa. *Biogas.* InTech.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J., Guwy, A., Kalyuzhnyi, S., Jenicek, P. & Lier, J. V. 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays.

Anozie, A., Layokun, S. & Okeke, C. 2005. An evaluation of a batch pilot-scale digester for gas production from agricultural wastes. *Energy Sources,* 27**,** 1301-1311.

Antoniou, P., Hamilton, J., Koopman, B., Jain, R., Holloway, B., Lyberatos, G. & Svoronos, S. 1990. Effect of temperature and pH on the effective maximum specific growth rate of nitrifying bacteria. *Water Research,* 24**,** 97-101.

Appels, L., Lauwers, J., Degrève, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J. & Dewil, R. 2011. Anaerobic digestion in global bio-energy production: potential and research challenges. *Renewable and Sustainable Energy Reviews,* 15**,** 4295-4301.

Arc.Cassava. 2014. *South African:Institute for Industrial Crops, Agricultural Research Council of South Africa* [Online]. Available: www.arc.agric.za/arc-iic/Pages/Cassava.aspx [Accessed 23 July 2018].

Arsova, L. 2011. *Anaerobic digestion of food waste: Current status, problems and an alternative product.* MSc Degree, Columbia University. Columbia University.

Assegid, B. 2014. *Biogas Production from Co-Digestion of Cow Dung and Banana Peels.* Master of Science in Biotechnology, Haramaya University. Ethiopia.

Assessment, G. E. 2012. Global Energy Assessment—toward a sustainable future. *Cambridge, UK, and Laxenburg, Austria: Cambridge University Press and the International Institute for Applied Systems Analysis*.

Astals, S., Batstone, D., Mata-Alvarez, J. & Jensen, P. 2014. Identification of synergistic impacts during anaerobic co-digestion of organic wastes. *Bioresource technology,* 169**,** 421-427.

Ayu, O. & Dyan Aryati, V. 2010. Biogas production using anaerobic biodigester from cassava starch effluent with ruminant bacteria as biocatalyst.

Babatunde, D. E., Babatunde, O. M., Akinbulire, T. O. & Oluseyi, P. O. 2018. Hybrid Energy Systems Model with the Inclusion of Energy Efficiency Measures: A Rural Application Perspective. *International Journal of Energy Economics and Policy,* 8**,** 310-323.

Bailey, J. & Ollis, D. 1986. Applied enzyme catalysis. *Biochemical engineering fundamentals,* 2**,** 157-227.

Balsam, J. & Ryan, D. 2006. Anaerobic digestion of animal wastes: factors to consider. *ATTRA-national sustainable agriculture information service. United States Department of Agriculture's, USA*.

Baltrenas, P. & Kvasauskas, M. 2008. Experimental investigation of biogas production using fatty waste. *Journal of Environmental Engineering and Landscape Management,* 16**,** 178-187.

Beaudin, M., Zareipour, H., Schellenberglabe, A. & Rosehart, W. 2010. Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for sustainable development,* 14**,** 302-314.

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I. & Williams, M. 2015. Feeding 9 billion by 2050–Putting fish back on the menu. *Food Security,* 7**,** 261-274.

Bhorat, H. 2015. *FactCheck: Is South Africa the most unequal society in the world* [Online]. South Africa: The Conversation. Available: http://theconversation.com/factcheck-is-south-africa-the-most-unequal-society-in-the-world-48334 [Accessed 30 September 2015].

Biswas, J., Chowdhury, R. & Bhattacharya, P. 2007. Mathematical modeling for the prediction of biogas generation characteristics of an anaerobic digester based on food/vegetable residues. *Biomass and Bioenergy,* 31**,** 80-86.

Biswas, R., Ahring, B. & Uellendahl, H. 2012. Improving biogas yields using an innovative pretreatment concept for conversion of the fiber fraction of manure. *Water science and technology : a journal of the International Association on Water Pollution Research,* 66**,** 1751-8.

Bohutskyi, P. & Bouwer, E. 2013. Biogas production from algae and cyanobacteria through anaerobic digestion: a review, analysis, and research needs. *In:* LEE, J. W. (ed.) *Advanced Biofuels and Bioproducts.* Springer. New York, 873-975.

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

Bozkurt, H., Van Loosdrecht, M. C., Gernaey, K. V. & Sin, G. 2016. Optimal WWTP process selection for treatment of domestic wastewater–A realistic full-scale retrofitting study. *Chemical Engineering Journal,* 286**,** 447-458.

Bożym, M., Florczak, I., Zdanowska, P., Wojdalski, J. & Klimkiewicz, M. 2015. An analysis of metal concentrations in food wastes for biogas production. *Renewable Energy,* 77**,** 467-472.

Branche, E. 2017. The multipurpose water uses of hydropower reservoir: The SHARE concept. *Comptes Rendus Physique,* 18**,** 469-478.

Braun, R., Weiland, P. & Wellinger, A. 2008. Biogas from energy crop digestion. *IEA Bioenergy Task,* 37**,** 1-20.

Brown, D. & Li, Y. 2012. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. *Bioresource technology*.

Brown, V. J. 2006. Biogas: a bright idea for Africa. *Environmental health perspectives,* 114**,** A300.

Bruni, E., Jensen, A. P., Pedersen, E. S. & Angelidaki, I. 2010. Anaerobic digestion of maize focusing on variety, harvest time and pretreatment. *Applied energy,* 87**,** 2212-2217.

Budiyono, B., Widiasa, I. N., Johari, S. & Sunarso, S. 2013. Increasing biogas production rate from cattle manure using rumen fluid as inoculums. *International Journal of Science and Engineering,* 6**,** 31-38.

Burton, S., Cohen, B., Harrison, S., Pather-Elias, S., Stafford, W., Van Hille, R. & Von Blottnitz, H. 2009. Energy from Wastewater-a Feasibility study. *WRC, South Africa*.

Buswell, A. M. & Neave, S. L. 1930. Laboratory studies of sludge digestion. *Bulletin (Illinois State Water Survey) no. 30*.

Campbell, C. J. & Wöstmann, A. 2013. *Campbell's atlas of oil and gas depletion*, Springer.

Carter, S., Fresco, L., Jones, P. & Fairbairn, J. 1993. *Introduction and diffusion of cassava in Africa*, Unknown Publisher.

Castrillón, L., Fernández-Nava, Y., Ormaechea, P. & Marañón, E. 2011. Optimization of biogas production from cattle manure by pre-treatment with ultrasound and co-digestion with crude glycerin. *Bioresource technology,* 102**,** 7845-7849.

Cecchi, F., Traverso, P. & Cescon, P. 1986. Anaerobic digestion of organic fraction of municipal solid wastes—digester performance. *Science of the Total Environment,* 56**,** 183-197.

Chandra, R., Takeuchi, H. & Hasegawa, T. 2012. Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. Renew. *Sustain. Energy Reviews*.

Change, I. P. O. C. 2007. Climate change 2007: The physical science basis. *Agenda,* 6**,** 333.

Cheng, S., Li, Z., Mang, H.-P., Huba, E.-M., Gao, R. & Wang, X. 2014. Development and application of prefabricated biogas digesters in developing countries. *Renewable and sustainable energy reviews,* 34**,** 387-400.

Choi, Y.-J. & Lee, S.-R. 2015. Review of database configuration of manure characteristics, analysis methods, bio-methane potential test for high solid manure recycling. *Journal of Animal Environmental Science,* 21**,** 9-20.

Christy, P. M., Gopinath, L. & Divya, D. 2014. A review on anaerobic decomposition and enhancement of biogas production through enzymes and microorganisms. *Renewable and Sustainable Energy Reviews,* 34**,** 167-173.

Chu, S. & Majumdar, A. 2012. Opportunities and challenges for a sustainable energy future. *nature,* 488**,** 294-303.

Chynoweth, D., Dolenc, D., Ghosh, S., Henry, M., Jerger, D. & Srivastava, V. 1982. Kinetics and advanced digester design for anaerobic digestion of water hyacinth and primary sludge. Biotechnol Bioeng Symp, 11 May 1982. Chicago, IL: Inst of Gas Tech, 381-398.

Chynoweth, D., Turick, C., Owens, J., Jerger, D. & Peck, M. 1993. Biochemical methane potential of biomass and waste feedstocks. *Biomass and bioenergy,* 5**,** 95-111.

Comino, E., Riggio, V. A. & Rosso, M. 2012. Biogas production by anaerobic co-digestion of cattle slurry and cheese whey. *Bioresource technology,* 114**,** 46-53.

Council, W. E. 2016. World energy resources 2016. *World Energy Council, London, UK*.

Dar, G. H. & Tandon, S. 1987. Biogas production from pretreated wheat straw, lantana residue, apple and peach leaf litter with cattle dung. *Biological wastes,* 21**,** 75-83.

Davidsson, Å., Lövstedt, C., La Cour Jansen, J., Gruvberger, C. & Aspegren, H. 2008. Co-digestion of grease trap sludge and sewage sludge. *Waste Management,* 28**,** 986-992.

De Meester, S., Demeyer, J., Velghe, F., Peene, A., Van Langenhove, H. & Dewulf, J. 2012. The environmental sustainability of anaerobic digestion as a biomass valorization technology. *Bioresource technology,* 121**,** 396-403.

De Vrieze, J., Hennebel, T., Boon, N. & Verstraete, W. 2012. Methanosarcina: The rediscovered methanogen for heavy duty biomethanation. *Bioresource technology,* 112**,** 1-9.

Dekanić, I., Maurović, L. & Karasalihović, D. Visions For Sustainability In Croatia. Energija i okoliš 2002, 2002.

Demetriades, P. 2008. *Thermal pre-treatment of cellulose rich biomass for biogas production.* slu.

Demirel, B. & Scherer, P. 2008. The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: a review. *Reviews in Environmental Science and Bio/Technology,* 7**,** 173-190.

Di Maria, F., Sordi, A., Cirulli, G., Gigliotti, G., Massaccesi, L. & Cucina, M. 2014. Co-treatment of fruit and vegetable waste in sludge digesters. An analysis of the relationship among bio-methane generation, process stability and digestate phytotoxicity. *Waste Management,* 34**,** 1603-1608.

Diaz-Chavez, R., Mutimba, S., Watson, H., Rodriguez-Sanchez, S. & Nguer, M. 2010. Mapping Food and Bioenergy in Africa. A report prepared on behalf of FARA. Forum for Agricultural Research in Africa. Ghana. *ERA-ARD, SROs, FARA***,** 3.

Dussadee, N., Unpaprom, Y. & Ramaraj, R. 2016. Grass Silage for Biogas Production. *Advances in Silage Production and Utilization.* InTech.

Eastman, J. & Ferguson, J. 1981. Solubilization of particulate organic carbon during the acid phase of anaerobic digestion. *Journal (Water Pollution Control Federation)***,** 352-366.

Eaton, A., Clesceri, L. S., Rice, E. W., Greenberg, A. E. & Franson, M. 2005. APHA: Standard Methods for the Examination of Water and Wastewater. *Centennial Edition., APHA, AWWA, WEF, Washington, DC*.

Ebner, J. H., Labatut, R. A., Lodge, J. S., Williamson, A. A. & Trabold, T. A. 2016. Anaerobic co-digestion of commercial food waste and dairy manure: Characterizing biochemical parameters and synergistic effects. *Waste Management,* 52**,** 286-294.

Ebrahimi-Nik, M., Heidari, A., Azghandi, S. R., Mohammadi, F. A. & Younesi, H. 2018. Drinking water treatment sludge as an effective additive for biogas production from food waste; kinetic evaluation and biomethane potential test. *Bioresource technology,* 260**,** 421-426.

Energypedia. 2016. *Fixed-dome Biogas Plants* [Online]. [Accessed 24-02- 2019].

Esi-Africa. 2016. *Biogas South Africa's great untapped potential* [Online]. Available: https://www.esi-africa.com/magazine_articles [Accessed 01-02-2019].

Esposito, G., Frunzo, L., Liotta, F., Panico, A. & Pirozzi, F. 2012. Bio-methane potential tests to measure the biogas production from the digestion and co-digestion of complex organic substrates. *The Open Environmental Engineering Journal,* 5.

Ezekoye, V. 2008. Anaerobic Digestion of Cassava Peels in Batch-Operated Plastic Biodigester and the Use of Stored Biogas for Heating. *Journal of Home Economics Research,* 9**,** 104-113.

Fang, C., Angelidaki, I. & Boe, K. 2010. *Biogas production from food-processing industrial wastes by anaerobic digestion*, Technical University of Denmark, Department of Environmental Engineering.

Faostat. 2018. *Food and Agricultural Organisation (FAO) of the United Nations* [Online]. Available: www.fao.org [Accessed 25 March 2018].

Federation, W. E. & Association, A. P. H. 2005. Standard methods for the examination of water and wastewater. *American Public Health Association (APHA): Washington, DC, USA*.

Florentino, H. D. O. 2003. Mathematical tool to size rural digesters. *Scientia Agricola,* 60**,** 185-190.

Forday, W. & Greenfield, P. F. 1983. Anaerobic digestion. *Effluent and Water Treatment Journal,* 23**,** 405-413.

Forgács, G. 2012. *Biogas production from citrus wastes and chicken feather: pretreatment and co-digestion*, Chalmers University of Technology.

Franco, A., Mosquera-Corral, A., Campos, J. & Roca, E. 2007. Learning to operate anaerobic bioreactors. *University of Santiago de Compostela, Available online: www. formatex. org*.

Franks, L., Euston-Brown, M., Ferry, A. & Giljova, S. 2015. Municipal waste water treatment works-Biogas to energy (co-generation).

Fry, J. 1988. Determination of biomass. *Methods in aquatic bacteriology. Wiley*, 27-72.

Galarraga, I., González-Eguino, M. & Markandya, A. 2011. *Handbook of sustainable energy*, Edward Elgar Publishing.

Gales, P. 1990. Malt beverages and brewing materials. *Official Methods of Analysis of the Association of Official Analytical Chemists,* 15**,** 708-715.

Garcin, C. & Burton, S. 2007. *Implementation of a generic membrane-based system for beneficiation and treatment of agro-industrial wastewater*, Water Research Commission Pretoria.

Ge, X., Matsumoto, T., Keith, L. & Li, Y. 2014. Biogas energy production from tropical biomass wastes by anaerobic digestion. *Bioresource technology,* 169**,** 38-44.

Gelegenis, J., Georgakakis, D., Angelidaki, I. & Mavris, V. 2007. Optimization of biogas production by co-digesting whey with diluted poultry manure. *Renewable Energy,* 32**,** 2147-2160.

Gerardi, M. H. 2003. *The microbiology of anaerobic digesters*, John Wiley & Sons. USA

Gerbens-Leenes, W., Hoekstra, A. Y. & Van Der Meer, T. H. 2009. The water footprint of bioenergy. *Proceedings of the National Academy of Sciences,* 106**,** 10219-10223.

Gerber, M. & Span, R. 2008. An analysis of available mathematical models for anaerobic digestion of organic substances for production of biogas. *Proceedings of the International Gas Union Research Conference,* 2**,** 1-30.

Ghosh, S. 2000. Bioconversion of water Hyacinth Coastal Bermuda grass MSW-Sludge blends to Methane Biotechnology and Bioengineering Symposium.

Gilson, E. 2017. Biogas production potential and cost-benefit analysis of harvesting wetland plants (Phragmites australis and Glyceria maxima).

Girija, D., Deepa, K., Xavier, F., Antony, I. & Shidhi, P. 2013. Analysis of cow dung microbiota—a metagenomic approach.

Girotto, F., Alibardi, L. & Cossu, R. 2015. Food waste generation and industrial uses: A review. *Waste management,* 45**,** 32-41.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M. & Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *science*, 1185383.

Goemans, R. 2017. The Development of the Biogas Industry in South Africa. Delft University of Technology, The Netherlands.

Gogela, U., Salie, Y., Pineo, C. & Basson, L. 2017. The business case for biogas from solid waste in the Western Cape. Green Cape, South Africa.

Gunaseelan, V. N. 1988. Anaerobic digestion of Gliricidia leaves for biogas and organic manure. *Biomass,* 17, 1-11.

Gunaseelan, V. N. 1994. Methane production from Parthenium hysterophorus L., a terrestrial weed, in semi-continuous fermenters. *Biomass and Bioenergy,* 6, 391-398.

Gunaseelan, V. N. 1995. Effect of inoculum/substrate ratio and pretreatments on methane yield from Parthenium. *Biomass and Bioenergy,* 8, 39-44.

Gunaseelan, V. N. 1997. Anaerobic digestion of biomass for methane production: a review. *Biomass and bioenergy,* 13, 83-114.

Gunaseelan, V. N. 2004. Biochemical methane potential of fruits and vegetable solid waste feedstocks. *Biomass and bioenergy,* 26, 389-399.

Gunaseelan, V. N. 2007. Regression models of ultimate methane yields of fruits and vegetable solid wastes, sorghum and napiergrass on chemical composition. *Bioresource technology,* 98, 1270-1277.

Gunaseelan, V. N. & Lakshmanaperumalsamy, P. 1990. Biogas production potential of Parthenium. *Biological Wastes,* 33, 311-314.

Haggblade, S., Andersson Djurfeldt, A., Banda Nyirenda, D., Bergman Lodin, J., Brimer, L., Chiona, M., Chitundu, M., Chiwona-Karltun, L., Cuambe, C. & Dolislager, M. 2012. Cassava commercialization in Southeastern Africa. *Journal of Agribusiness in Developing and Emerging Economies,* 2, 4-40.

Hagos, K., Zong, J., Li, D., Liu, C. & Lu, X. 2017. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. *Renewable and Sustainable Energy Reviews,* 76, 1485-1496.

Haider, M. R., Yousaf, S., Malik, R. N. & Visvanathan, C. 2015. Effect of mixing ratio of food waste and rice husk co-digestion and substrate to inoculum ratio on biogas production. *Bioresource technology,* 190, 451-457.

Hall, D. O., Barnard, G. W. & Moss, P. 1982. *Biomass for energy in the developing countries: Current Role, Potential, Problems, Prospects*, Elsevier.

Hamilton, D. W. 2014. Anaerobic digestion of animal manures: understanding the basic processes. *Biosystems and Agricultural Engineering*.

Hansson, G. 1981. *Methane fermentations: end product inhibition, thermophilic methane formation and production of methane from algae.* Doctoral dissertation, Lund University. Sweden.

Hartmann, H., Angelidaki, I. & Ahring, B. K. 2002. Co-digestion of the organic fraction of municipal waste with other waste types. *Biomethanization of the organic fraction of municipal solid wastes.* IWA Publishing. 181-200.

Hasan, M., Mahlia, T. & Nur, H. 2012. A review on energy scenario and sustainable energy in Indonesia. *Renewable and Sustainable Energy Reviews,* 16**,** 2316-2328.

Hashimoto, A. G. 1986. Pretreatment of wheat straw for fermentation to methane. *Biotechnology and bioengineering,* 28**,** 1857-1866.

Hassan, K., Zubairu, M. & Husaini, I. 2015. Biogas production using cow dung, poultry waste and yam peels. *Int. J. Environ. Bioenergy,* 10**,** 107-114.

Heeg, K., Pohl, M., Sontag, M., Mumme, J., Klocke, M. & Nettmann, E. 2014. Microbial communities involved in biogas production from wheat straw as the sole substrate within a two-phase solid-state anaerobic digestion. *Systematic and applied microbiology,* 37**,** 590-600.

Helrich, K. 1990. *Official methods of Analysis of the AOAC. Volume 2*, Association of Official Analytical Chemists Inc.

Hettiaratchi, P., Jayasinghe, P., H Tay, J. & Yadav, S. 2015. Recent advances of biomass waste to gas using landfill bioreactor technology-a review. *Current Organic Chemistry,* 19**,** 413-422.

Heubaum, H. & Biermann, F. 2015. Integrating global energy and climate governance: The changing role of the International Energy Agency. *Energy Policy,* 87**,** 229-239.

Hillocks, R. J., Thresh, J. & Bellotti, A. 2002. *Cassava: biology, production and utilization*, CABI.

Hills, D. & Roberts, D. 1982. Conversion of tomato, peach and honeydew solid waste into methane gas. *Transactions of the ASAE,* 25**,** 820-0826.

Hinken, L., Urban, I., Haun, E., Weichgrebe, D. & Rosenwinkel, K. 2008. The valuation of malnutrition in the mono-digestion of maize silage by anaerobic batch tests.

Hiv/Aids Junpo & Organization, W. H. 2007. *AIDS epidemic update*, World Health Organization.

Hoban, D. & Berg, L. 1979. Effect of iron on conversion of acetic acid to methane during methanogenic fermentations. *Journal of Applied bacteriology,* 47**,** 153-159.

Hoegh-Guldberg, O. & Bruno, J. F. 2010. The impact of climate change on the world's marine ecosystems. *Science,* 328**,** 1523-1528.

Hutchings, T., Moffat, A. & Kemp, R. 2001. Effects of rooting and tree growth of selected woodland species on cap integrity in a mineral capped landfill site. *Waste management & research,* 19**,** 194-200.

Ighravwe, D., Babatunde, O., Adedoja, O. & Okharedia, T. 2018. Evaluation and Selection of Hybrid Renewable Energy Systems for Healthcare Centres In Rural Areas: A Techno-economic Approach. IEEE 7th International Conference on Adaptive Science & Technology (ICAST), August 2018 University of Ghana, Greater Accra. Ghana: IEEE, 1-7.

Ighravwe, D. E. & Babatunde, M. O. 2018. Determination of a Suitable Renewable Energy Source for Mini-Grid Business: A Risk-Based Multicriteria Approach. *Journal of Renewable Energy,* 2018.

Igwe, N. J. 2014. Production of Biogas From Cassava and Plantain Peels Blended with cowdung. *International Journal of Life Sciences Biotechnology and Pharma Research,* 3**,** 201-213.

Ituen, E., John, N. & Bassey, B. 2009. Biogas production from organic waste in Akwa Ibom State of Nigeria. *Appropriate Technologies for Environmental Protection in the Developing World.* Springer. Dordrecht, 93-99.

Izumi, K., Okishio, Y.-K., Nagao, N., Niwa, C., Yamamoto, S. & Toda, T. 2010. Effects of particle size on anaerobic digestion of food waste. *International biodeterioration & biodegradation,* 64**,** 601-608.

Jamal, N. 2015. Options for the supply of electricity to rural homes in South Africa. *Journal of Energy in Southern Africa,* 26**,** 58-65.

Jansson, C., Westerbergh, A., Zhang, J., Hu, X. & Sun, C. 2009. Cassava, a potential biofuel crop in (the) People’s Republic of China. *Applied Energy,* 86**,** S95-S99.

Jekayinfa, S. O. & Scholz, V. 2013. Laboratory Scale Preparation of Biogas from Cassava Tubers, Cassava Peels, and Palm Kernel Oil Residues. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* 35**,** 2022-2032.

Jewitt, G., Wen, H., Kunz, R. & Rooyen, A. V. 2009. Scoping study on water use of crops/trees for biofuels in South Africa. *WRC Report*.

Jiang, H., Qin, Y., Gadow, S., Ohnishi, A., Fujimoto, N. & Li, Y.-Y. 2018. Bio-hythane production from cassava residue by two-stage fermentative process with recirculation. *Bioresource Technology,* 247**,** 769-775.

Jingura, R. M. & Kamusoko, R. 2017. Methods for determination of biomethane potential of feedstocks: a review. *Biofuel Research Journal,* 4**,** 573-586.

Jingura, R. M. & Matengaifa, R. 2009. Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe. *Renewable and Sustainable Energy Reviews,* 13**,** 1116-1120.

Jordaan, G. P. 2018. *Evaluating the sustainable potential of biogas generation in South Africa.* Stellenbosch University. South Africa.

Jørgensen, P. J. 2009. *Biogas-green energy.* Aarhus University. Tjele, Denmark.

Judkins, R. R., Fulkerson, W. & Sanghvi, M. K. 1993. The dilemma of fossil fuel use and global climate change. *Energy & fuels,* 7**,** 14-22.

Kalia, A. K. & Kanwar, S. S. 1990. Anaerobic fermentation of Ageratum for biogas production. *Biological wastes,* 32**,** 155-158.

Kalyuzhnyi, S., Veeken, A. & Hamelers, B. 2000. Two-particle model of anaerobic solid state fermentation. *Water Science & Technology,* 41**,** 43-40.

Kannan, N. & Vakeesan, D. 2016. Solar energy for future world:-A review. *Renewable and Sustainable Energy Reviews,* 62**,** 1092-1105.

Kanwar, S. & Guleri, R. 1995. Biogas production from mixture of poultry litter and cattle dung with an acclimatised inoculum. Biogas Forum I (60), 1995. 21-23.

Karp, S. G., Woiciechowski, A. L., Soccol, V. T. & Soccol, C. R. 2013. Pretreatment strategies for delignification of sugarcane bagasse: a review. *Brazilian archives of biology and technology,* 56**,** 679-689.

Kaur, H. & Kumar, S. 2017. Designing of small scale fixed dome biogas digester for paddy straw. *International Journal of Renewable Energy Research (IJRER),* 7**,** 422-431.

Keay, G. 1981. Anaerobic digestion: design and upgrading. Sewage Treatment plants, design, operation and upgrading, University of Pretoria. South Africa, 1-18.

Kennedy, N., Yorgey, G., Frear, C. & Kruger, C. E. 2015. *On-farm co-digestion of dairy manure with high energy organics: stakeholder interviews and literature review*, Washington State University Extension. USA

Khalid, A., Arshad, M., Anjum, M., Mahmood, T. & Dawson, L. 2011. The anaerobic digestion of solid organic waste. *Waste management,* 31**,** 1737-1744.

Khamis, G. & Papenbrock, J. 2014. Newly established drought-tolerant plants as renewable primary products as source of bioenergy. *Emirates Journal of Food and Agriculture,* 26**,** 1067.

Khan, N., Le Roes-Hill, M., Welz, P. J., Grandin, K. A., Kudanga, T., Van Dyk, J. S., Ohlhoff, C., Van Zyl, W. & Pletschke, B. I. 2015. Fruit waste streams in South Africa and their potential role in developing a bio-economy. *South African Journal of Science,* 111**,** 1-11.

Khanal, S. K. 2008. Anaerobic biotechnology for bioenergy production. *Principles and Applications. A john Wiley & Sons, Ltd. Publication, USA,* 20**,** 385-406.

Kigozi, R., Aboyade, A. & Muzenda, E. 2014. Biogas production using the organic fraction of municipal solid waste as feedstock. *World,* 5**,** 6.

Klimiuk, E., Pokój, T., Budzyński, W. & Dubis, B. 2010. Theoretical and observed biogas production from plant biomass of different fibre contents. *Bioresource technology,* 101**,** 9527-9535.

Knol, W., Van Der Most, M. M. & De Waart, J. 1978. Biogas production by anaerobic digestion of fruit and vegetable waste. A preliminary study. *Journal of the Science of Food and Agriculture,* 29**,** 822-830.

Kondusamy, D. & Kalamdhad, A. S. 2014. Pre-treatment and anaerobic digestion of food waste for high rate methane production–A review. *Journal of Environmental Chemical Engineering,* 2**,** 1821-1830.

Kong, X., Wei, Y., Xu, S., Liu, J., Li, H., Liu, Y. & Yu, S. 2016. Inhibiting excessive acidification using zero-valent iron in anaerobic digestion of food waste at high organic load rates. *Bioresource technology,* 211**,** 65-71.

Kougias, P. & Angelidaki, I. 2018. Biogas and its opportunities—A review. *Frontiers of Environmental Science & Engineering,* 12.

Kuiper, L., Ekmekci, B., Hamelinck, C., Hettinga, W., Meyer, S. & Koop, K. 2007. Bio-ethanol from Cassava. Ecofys Netherlands BV. Project Number PBIONL062937.

Kumar, A., Mandal, B. & Sharma, A. 2015. Advancement in Biogas Digester. *Energy Sustainability Through Green Energy.* Springer. New Delhi, 351-382.

Kwietniewska, E. & Tys, J. 2014. Process characteristics, inhibition factors and methane yields of anaerobic digestion process, with particular focus on microalgal biomass fermentation. *Renewable and Sustainable Energy Reviews,* 34**,** 491-500.

Labatut, R. A., Angenent, L. T. & Scott, N. R. 2011. Biochemical methane potential and biodegradability of complex organic substrates. *Bioresource Technology,* 102**,** 2255-2264.

Lebuhn, M., Liu, F., Heuwinkel, H. & Gronauer, A. 2008. Biogas production from mono-digestion of maize silage-long-term process stability and requirements. *Water science and technology : a journal of the International Association on Water Pollution Research,* 58**,** 1645-51.

Lee, D. 2007. *Composition of herbaceous biomass feedstocks*, North Central Sun Grant Center, South Dakota State University.

Lehtomaki, A. 2006. *Biogas Production From Energy Crops and Crop Residues.* University of Jyvaskyla. Finland.

Lemmer, A. & Oechsner, H. Use of grass or field crops for biogas production. Proc. AgEng, 2002.

Lettinga, G. 1995. Anaerobic digestion and wastewater treatment systems. *Antonie van leeuwenhoek,* 67**,** 3-28.

Lettinga, G., Field, J., Van Lier, J., Zeeman, G. & Pol, L. H. 1997. Advanced anaerobic wastewater treatment in the near future. *Water Science and Technology,* 35**,** 5-12.

Li, Y., Li, Y., Zhang, D., Li, G., Jiaxin, L. & Li, S. Solid state anaerobic co-digestion of tomato residues with dairy manure and corn stover for biogas production. Bioresource Technology, 2016. 50-55.

Li, Y., Park, S. & Zhu, J. 2011. Solid-state anaerobic digestion for methane production from organic waste. *Renewable and sustainable energy reviews,* 15**,** 821-826.

Li, Y., Zhang, R., Chen, C., Liu, G., He, Y. & Liu, X. 2013. Biogas production from co-digestion of corn stover and chicken manure under anaerobic wet, hemi-solid, and solid state conditions. *Bioresource technology,* 149**,** 406-412.

Liew, L. N. 2011. *Solid-state anaerobic digestion of lignocellulosic biomass for biogas production.* The Ohio State University.

Lim, J. S., Manan, Z. A., Alwi, S. R. W. & Hashim, H. 2012. A review on utilisation of biomass from rice industry as a source of renewable energy. *Renewable and Sustainable Energy Reviews,* 16**,** 3084-3094.

Linnerud, K., Mideksa, T. K. & Eskeland, G. S. 2011. The impact of climate change on nuclear power supply. *The Energy Journal***,** 149-168.

Linville, J. L., Shen, Y., Wu, M. M. & Urgun-Demirtas, M. 2015. Current State of Anaerobic Digestion of Organic Wastes in North America. *Current Sustainable/Renewable Energy Reports,* 2**,** 136-144.

Liu, C.-F., Yuan, X.-Z., Zeng, G.-M., Li, W.-W. & Li, J. 2008. Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. *Bioresource Technology,* 99**,** 882-888.

Liu, T., Sun, L., Müller, B. & Schnürer, A. 2017. Importance of inoculum source and initial community structure for biogas production from agricultural substrates. *Bioresource Technology,* 245**,** 768-777.

Liu, X. L., Wang, M. M., Hu, X. J. & Song, Y. H. 2014. Effect of Total Solids Content on the Biogas Production and Phosphorus Release from Excess Sludge. *Advanced Materials Research,* 1010-1012**,** 1006-1009.

Liu, Y., Dong, J., Liu, G., Yang, H., Liu, W., Wang, L., Kong, C., Zheng, D., Yang, J. & Deng, L. 2015. Co-digestion of tobacco waste with different agricultural biomass feedstocks and the inhibition of tobacco viruses by anaerobic digestion. *Bioresource technology,* 189**,** 210-216.

López-Bellido, L., Wery, J. & López-Bellido, R. J. 2014. Energy crops: prospects in the context of sustainable agriculture. *European journal of agronomy,* 60**,** 1-12.

Low, S. C. 2014. *Mixing characteristics of a model anaerobic digester.* Doctor of Philosophy, RMIT University. Australia.

Luna-Delrisco, M., Normak, A. & Orupold, K. 2011. Biochemical methane potential of different organic wastes and energy crops from Estonia. *Agronomy Research,* 9**,** 331-342.

Lyilade, Y. 2009. *An investigation into the mechanical biological pretreatment of garden waste using forced aeration and its impact on carbon emissions reduction potential.* MSc Eng, UKZN. UKZN.

Lynd, L., Von Blottnitz, H., Tait, B., De Boer, J., Pretorius, I., Rumbold, K. & Van Zyl, W. 2003. Converting plant biomass to fuels and commodity chemicals in South Africa: a third chapter?: science policy. *South African Journal of Science,* 99**,** p. 499-507.

Maamri, S. & Amrani, M. 2014. Biogas production from waste activated sludge using cattle dung inoculums: Effect of total solid contents and kinetics study. *Energy Procedia,* 50**,** 352-359.

Madlener, R. & Sunak, Y. 2011. Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? *Sustainable Cities and Society,* 1**,** 45-53.

Mahamat, A., Gourdon, R., Leger, P. & Vermande, P. 1989. Methane recovery by anaerobic digestion of cellulosic materials available in Sahel. *Biological wastes,* 30**,** 181-197.

Mahar, R. B., Liu, J., Yue, D. & Nie, Y. 2007. Biodegradation of organic matters from mixed unshredded municipal solid waste through air convection before landfilling. *Journal of the Air & Waste Management Association,* 57**,** 39-46.

Malakahmad, A., Basri, N. E. A., Zain, S. M., Kutty, S. R. M. & Isa, M. H. 2009. Overview on the development of anaerobic digestion for kitchen waste in Malaysia. *Green Technology* 7**,** 21.

Maltsoglou, I., Koizumi, T. & Felix, E. 2013. The status of bioenergy development in developing countries. *Global Food Security,* 2**,** 104-109.

Mara, D. & Horan, N. J. 2003. *Handbook of water and wastewater microbiology*, Elsevier.

Maragkaki, A., Fountoulakis, M., Kyriakou, A., Lasaridi, K. & Manios, T. 2018. Boosting biogas production from sewage sludge by adding small amount of agro-industrial by-products and food waste residues. *Waste Management,* 71**,** 605-611.

Marrison, C. & Larson, E. 1996. A preliminary analysis of the biomass energy production potential in Africa in 2025 considering projected land needs for food production. *Biomass and Bioenergy,* 10**,** 337-351.

Martens, E. C., Koropatkin, N. M., Smith, T. J. & Gordon, J. I. 2009. Complex glycan catabolism by the human gut microbiota: the Bacteroidetes Sus-like paradigm. *Journal of Biological Chemistry*, jbc. R109. 022848.

Mata-Alvarez, J. 2002. *Biomethanization of the organic fraction of municipal solid wastes*, IWA publishing.

Mata-Alvarez, J., Cecchi, F., Pavan, P. & Llabres, P. 1990. The performances of digesters treating the organic fraction of municipal solid wastes differently sorted. *Biological wastes,* 33, 181-199.

Mcbride, D. M. 2012. *The process of research in psychology*, Sage.

Mccarty, P. L. & Smith, D. P. 1986. Anaerobic wastewater treatment. *Environmental science & technology,* 20, 1200-1206.

Mckendry, P. 2002. Energy production from biomass (part 2): conversion technologies. *Bioresource technology,* 83, 47-54.

Mel, M., Ihsan, S. I. & Setyobudi, R. H. 2015. Process Improvement of Biogas Production from Anaerobic Co-digestion of Cow Dung and Corn Husk. *Procedia Chemistry,* 14, 91-100.

Memon, M., Memon, K., Mirani, S. & Jamro, G. 2012. Comparative evaluation of organic wastes for improving maize growth and NPK content. *African journal of biotechnology,* 11, 9343-9349.

Meshach, I. A. 2013. *Comparative Study Of Biogas Production From Cow Dung, Chicken Droppings And Cymbopogon Citratus As Alternative Energy Sources In Nigeria.* PhD Dissertation, Ahmadu Bello University. Zaria Nigeria.

Misevičius, A. & Baltrėnas, P. 2011. Experimental investigation of biogas production using biodegradable municipal waste. *Journal of Environmental Engineering and Landscape Management,* 19, 167-177.

Mital, K. M. 1996. *Biogas Systems: Principles and Applications*, New Age International. New Delhi

Mogami, C., Souza, C., Paim, V., Tinoco, I. & Gates, R. 2006. Methane concentration in biogas produced from dejections of milk goats fed with different diets. ASAE Annual Meeting, 2006. American Society of Agricultural and Biological Engineers, 1.

Molino, A., Larocca, V., Chianese, S. & Musmarra, D. 2018. Biofuels production by biomass gasification: A review. *Energies,* 11, 811.

Molino, A., Migliori, M., Ding, Y., Bikson, B., Giordano, G. & Braccio, G. 2013a. Biogas upgrading via membrane process: modelling of pilot plant scale and the end uses for the grid injection. *Fuel,* 107, 585-592.

Molino, A., Nanna, F., Ding, Y., Bikson, B. & Braccio, G. 2013b. Biomethane production by anaerobic digestion of organic waste. *Fuel,* 103, 1003-1009.

Morgan, N. K. & Choct, M. 2016. Cassava: Nutrient composition and nutritive value in poultry diets. *Animal Nutrition,* 2**,** 253-261.

Mshandete, A., Björnsson, L., Kivaisi, A. K., Rubindamayugi, M. S. & Mattiasson, B. 2006. Effect of particle size on biogas yield from sisal fibre waste. *Renewable energy,* 31**,** 2385-2392.

Munganga, G. 2013. Overviewof biogas market in South Africa.

Murphy, J., Braun, R., Weiland, P. & Wellinger, A. Biogas from crop digestion. IEA bioenergy task, 2011. 1-23.

Musango, J. K., Amigun, B. & Brent, A. C. 2011. Sustainable electricity generation technologies in South Africa: initiatives, challenges and policy implications. *Energy and Environment Research,* 1**,** p124.

Mutungwazi, A., Mukumba, P. & Makaka, G. 2018. Biogas digester types installed in South Africa: A review. *Renewable and Sustainable Energy Reviews,* 81**,** 172-180.

Naik, S. N., Goud, V. V., Rout, P. K. & Dalai, A. K. 2010. Production of first and second generation biofuels: a comprehensive review. *Renewable and sustainable energy reviews,* 14**,** 578-597.

Nallathambi Gunaseelan, V. 1997. Anaerobic digestion of biomass for methane production: a review. *Biomass and bioenergy,* 13**,** 83-114.

Nasir, A., Bala, K. C., Mohammed, S. N., Mohammed, A. & Umar, I. 2015. Experimental Investigation on the effects of digester size on biogas production from cow dung. *American journal of engineering research,* 4**,** 181-186.

Nekhubvi, V. & Tinarwo, D. 2017. Long-term temperature measurement: Biogas digesters fermenting slurry. *Journal of Energy in Southern Africa,* 28**,** 99-106.

Nges, I. A., Lovisa, B. & Hinrich, U. 2012. Anaerobic digestion of crop and waste biomass: Impact of feedstock characteristics on process performance.

Nijaguna, B. 2006. *Biogas Technology*, New Age International. New Dehli, India

Nipaney, P. & Panholzer, M. 1987. Influence of temperature on biogas production from Pistia stratiotes. *Biological wastes,* 19**,** 267-274.

Nnfcc. 2016. *The Official Information Portal on Anaerobic Digestion* [Online]. Available: http://www.biogas-info.co.uk/ [Accessed 17/11/2018].

Nuwamanya, E., Chiwona-Karltun, L., Kawuki, R. S. & Baguma, Y. 2012. Bio-ethanol production from non-food parts of cassava (Manihot esculenta Crantz). *Ambio,* 41**,** 262-270.

Odhiambo, N. M. 2009. Electricity consumption and economic growth in South Africa: A trivariate causality test. *Energy Economics,* 31**,** 635-640.

Odlare, M. 2005. *Organic residues-a resource for arable soils. 2005: Swedish University of Agricultural Sciences, Faculty of Natural Resources and Agricultural Sciences, Department of Microbiology.* PhD thesis.

Ogut, G. C., Konakli, B., Calicioglu, O., Erguder, T. H., Kaymak, B. & Demirer, G. N. 2013. Biogas generation from microalgal biomass and the effect of pretreatment. *Journal of Selcuk University Natural and Applied Science*, 872-881.

Okonkwo, P., Aderemi, B. & Okoli, C. 2013. Factors Affecting Biogas Production During Anaerobic Decomposition of Brewery Effluent-Wastewater in a Fluidized Bed Digester. *Journal of Environment and Earth Science,* 3, 32-40.

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

Oladeebo, J. & Oyetunde, O. 2013. Relationship between plot size and technical efficiency of cassava farms in Oyo State of Nigeria: A stochastic frontier analysis. *Int. J. Current Research,* 5, 2782-2786.

Omer, A. & Fadalla, Y. 2003. Biogas energy technology in Sudan. *Renewable Energy,* 28, 499-507.

Oparaku, N., Ofomatah, A. & Okoroigwe, E. 2013. Biodigestion of cassava peels blended with pig dung for methane generation. *African Journal of Biotechnology,* 12.

Ošlaj, M. & Muršec, B. 2010. Biogas as a renewable energy source. *Tehnicki Vjesnik,* 17, 109.

Owens, J. & Chynoweth, D. 1993. Biochemical methane potential of municipal solid waste (MSW) components. *Water Science and Technology,* 27, 1-14.

Owusu, P. A. & Asumadu-Sarkodie, S. 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering,* 3, 1167990.

Pagés-Díaz, J., Pereda-Reyes, I., Taherzadeh, M. J., Sárvári-Horváth, I. & Lundin, M. 2014. Anaerobic co-digestion of solid slaughterhouse wastes with agro-residues: synergistic and antagonistic interactions determined in batch digestion assays. *Chemical Engineering Journal,* 245, 89-98.

Panwar, N., Kaushik, S. & Kothari, S. 2011. Role of renewable energy sources in environmental protection: a review. *Renewable and Sustainable Energy Reviews,* 15, 1513-1524.

Panyadee, S., Petiraksakul, A. & Phalakornkule, C. 2013. Biogas production from co-digestion of Phyllanthus emblica residues and food waste. *Energy for Sustainable Development,* 17, 515-520.

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N. & Cecinato, A. 2018. Environmental impact of biogas: A short review of current knowledge. *Journal of Environmental Science and Health, Part A,* 53, 899-906.

Parawira, W., Murto, M., Zvauya, R. & Mattiasson, B. 2004. Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves. *Renewable Energy,* 29**,** 1811-1823.

Pavan, P., Bolzonella, D., Battistoni, E. & Cecchi, F. 2007. Anaerobic co-digestion of sludge with other organic wastes in small wastewater treatment plants: an economic considerations evaluation. *Water Science and Technology,* 56**,** 45-53.

Pegels, A. 2010. Renewable energy in South Africa: Potentials, barriers and options for support. *Energy policy,* 38**,** 4945-4954.

Pell, A. N., Schofield, P. & Pitt, R. E. 1994. Kinetics of fiber digestion from in vitro gas production. *Journal of Animal Science,* 72**,** 2980-2991.

Peres, S., Monteiro, M. R., Ferreira, M. L., Do Nascimento Junior, A. F. & Fernandez, M. D. L. a. P. 2018. Anaerobic Digestion Process for the Production of Biogas from Cassava and Sewage Treatment Plant Sludge in Brazil. *BioEnergy Research***,** 1-8.

Phetyim, N., Wanthong, T., Kannika, P. & Supngam, A. 2015. Biogas production from vegetable waste by using dog and cattle manure. *Energy Procedia,* 79**,** 436-441.

Pisano, G. 2007. *Nitrate removal using compost & Pine Bark as a carbon source.* MSc. Eng, University of KwaZulu-Natal. South Africa.

Popp, J., Lakner, Z., Harangi-Rákos, M. & Fári, M. 2014. The effect of bioenergy expansion: Food, energy, and environment. *Renewable and Sustainable Energy Reviews,* 32**,** 559-578.

Prakash, O., Kumar, A., Pandey, A., Kumar, A. & Laguri, V. 2005. A Review on Biogas Plant. *International Journal of New Technologies in Science and Engineering.* Nagulapalli, Visakhapatnam, India: Institute of Research in Engineering and Technology.

Prior, B. & Potgieter, H. 1981. Composition of Fruit and Vegetable Processing Wastes. *Water S. A.,* 7**,** 155-159.

Promphiphak, P. & Wongwuttanasatian, T. Biogas Production from Cassava Waste Cake in a Two-Stage Anaerobic Digestion System. Advanced Materials Research, 2012. Trans Tech Publ, 351-355.

Pulles, W., Van Niekerk, A., Wood, A., Batchelor, A., Dill, S., Du Plessis, P., Howie, D. & Casey, T. 2001. Pilot Scale Development of Integrated Passive Water Treatment Systems for Mine Effluent Streams. *WRC Report***,** 01.

Quadrelli, R. & Peterson, S. 2007. The energy–climate challenge: Recent trends in CO2 emissions from fuel combustion. *Energy policy,* 35**,** 5938-5952.

Radhika, L., Seshadri, S. & Mohandas, P. 1983. A study of biogas generation from coconut pith. *Journal of Chemical Technology and Biotechnology. Biotechnology,* 33**,** 189-194.

Rajendran, K., Aslanzadeh, S. & Taherzadeh, M. J. 2012. Household biogas digesters—A review. *Energies,* 5**,** 2911-2942.

Rilling, N. 2005. Anaerobic fermentation of wet and semidry garbage waste fractions. *Environmental Biotechnology: Concepts and Applications***,** 355-373.

Ritchie, H. & Roser, M. 2014. Energy Production and Changing Energy Sources. *Our World In Data*.

Rittmann, B. E. & Mccarty, P. L. 2012. *Environmental biotechnology: principles and applications*, Tata McGraw-Hill Education.

Roati, C., Fiore, S., Ruffino, B., Marchese, F., Novarino, D. & Zanetti, M. 2012. Preliminary evaluation of the potential biogas production of food-processing industrial wastes. *American Journal of Environmental Sciences,* 8**,** 291.

Rodrigues, A. L., Cruz, G., Souza, M. E. & Gomes, W. C. 2018. Application of cassava harvest residues (Manihot esculenta Crantz) in biochemical and thermochemical conversion process for bioenergy purposes: A literature review. *African Journal of Biotechnology,* 17**,** 37-50.

Rodriguez-Chiang, L. M. & Dahl, O. P. 2014. Effect of inoculum to substrate ratio on the methane potential of microcrystalline cellulose production wastewater. *BioResources,* 10**,** 898-911.

Sahoo, S. K. 2016. Renewable and sustainable energy reviews solar photovoltaic energy progress in India: A review. *Renewable and Sustainable Energy Reviews,* 59**,** 927-939.

Samer, M. 2012. Biogas plant constructions. *In:* KUMAR, S. (ed.) *Biogas.* InTech. 343-368.

Sarada, R. & Joseph, R. 1994. Studies on factors influencing methane production from tomato-processing waste. *Bioresource technology,* 47**,** 55-57.

Scano, E. A., Asquer, C., Pistis, A., Ortu, L., Demontis, V. & Cocco, D. 2014. Biogas from anaerobic digestion of fruit and vegetable wastes: experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant. *Energy Conversion and Management,* 77**,** 22-30.

Scherer, P., Neumann, L., Demirel, B., Schmidt, O. & Unbehauen, M. 2009. Long term fermentation studies about the nutritional requirements for biogasification of fodder beet silage as mono-substrate. *Biomass and Bioenergy,* 33**,** 873-881.

Schink, B. 1997. Energetics of syntrophic cooperation in methanogenic degradation. *Microbiology and Molecular Biology Reviews,* 61**,** 262-280.

Schnurer, A. & Jarvis, A. 2010. Microbiological handbook for biogas plants. *Swedish Waste Management U,* 2009**,** 1-74.

Scholtz, M., Van Ryssen, J., Meissner, H. & Laker, M. C. 2013. A South African perspective on livestock production in relation to greenhouse gases and water usage. *South African Journal of Animal Science,* 43**,** 247-254.

Seghezzo, L., Zeeman, G., Van Lier, J. B., Hamelers, H. & Lettinga, G. 1998. A review: the anaerobic treatment of sewage in UASB and EGSB reactors. *Bioresource Technology,* 65**,** 175-190.

Seppälä, M., Paavola, T. & Rintala, J. 2007. Methane yields of different grass species on the second and third harvest in boreal conditions. 11th IWA World Congress on Anaerobic Digestion, Brisbane, Australia, 2007. 23-27.

Shah, F. A., Mahmood, Q., Rashid, N., Pervez, A., Raja, I. A. & Shah, M. M. 2015. Co-digestion, pretreatment and digester design for enhanced methanogenesis. *Renewable and Sustainable Energy Reviews,* 42**,** 627-642.

Sharma, S. K., Mishra, I., Sharma, M. & Saini, J. 1988. Effect of particle size on biogas generation from biomass residues. *Biomass,* 17**,** 251-263.

Shen, F., Yuan, H., Pang, Y., Chen, S., Zhu, B., Zou, D., Liu, Y., Ma, J., Yu, L. & Li, X. 2013. Performances of anaerobic co-digestion of fruit & vegetable waste (FVW) and food waste (FW): single-phase vs. two-phase. *Bioresource technology,* 144**,** 80-85.

Shiralipour, A. & Smith, P. H. 1984. Conversion of biomass into methane gas. *Biomass,* 6**,** 85-92.

Shyam, M. & Sharma, P. 1994. Solid-state anaerobic digestion of cattle dung and agro-residues in small-capacity field digesters. *Bioresource Technology,* 48**,** 203-207.

Sichilalu, S., Lyandenga, P., Tazvinga, H., Wamalwa, F., Ngoyic, L., Mathaba, T., Wanjiru, E. & Xia, X. 2017. Experimental determination of a critical temperature for maximum anaerobic digester biogas production. *2017 International Multi-Disciplinary Conference.* Zambia Research and Development Centre, Lusaka, Zambia.

Sigge, G. & Britz, T. 2007. UASB treatment of a highly alkaline fruit-cannery lye-peeling wastewater. *Water Sa,* 33.

Silici, L., Bias, C. & Cavane, E. 2015. Sustainable agriculture for small-scale farmers in Mozambique. *Country report, International Institute for Environment and Development, London*.

Singh, O. V. & Harvey, S. P. 2010. *Sustainable Biotechnology: Sources of Renewable Energy*, Springer Netherlands

Sitorus, B. & Panjaitan, S. D. 2013. Biogas recovery from anaerobic digestion process of mixed fruit-vegetable wastes. *Energy Procedia,* 32**,** 176-182.

Smith, J., Austin, G., Avery, L. & Balana, B. 2011. The potential of small-scale biogas digesters to alleviate poverty and improve long term sustainability of ecosystem services in Sub-Saharan Africa. *Institute of Biological and Environmental Science, University of Aberdeen*.

Snyman, C. & Botha, W. 1993. Coal in south Africa. *Journal of African Earth Sciences (and the Middle East),* 16**,** 171-180.

Soccol, C. R., Faraco, V., Karp, S. G., Vandenberghe, L. P., Thomaz-Soccol, V., Woiciechowski, A. L. & Pandey, A. 2011. Lignocellulosic bioethanol: current status and future perspectives. *Biofuels.* Academic Press. Amsterdam, 101-122.

Solangi, K., Islam, M., Saidur, R., Rahim, N. & Fayaz, H. 2011. A review on global solar energy policy. *Renewable and sustainable energy reviews,* 15**,** 2149-2163.

Sorathia, H. S., Rathod, P. P. & Sorathiya, A. S. 2012. Biogas Generation and Factors Affecting the biogas Generation-A Review Study. *International Journal of Advanced Engineering Technology,* 3**,** 72-78.

Sorrell, S. 2015. Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews,* 47**,** 74-82.

Sparks, D., Madhlopa, A., Keen, S., Moorlach, M., Dane, A., Krog, P. & Dlamini, T. 2014. Renewable energy choices and their water requirements in South Africa. *Journal of Energy in Southern Africa,* 25**,** 80-92.

Speece, R. E. 1983. Anaerobic biotechnology for industrial wastewaters. *Environmental science & technology,* 17**,** 416A-427A.

Spencer, D. & Ezedinma, C. 2017. Cassava cultivation in sub-Saharan Africa. *Achieving sustainable cultivation of cassava.* 1. 123-148.

Sridevi, V. D., Srinivasan, S., Kayalvizhi, R. & Bhuvaneswari, R. 2012. Studies on conversion of carbohydrate content in the mixture of vegetable wastes into biogas in a single stage anaerobic reactor. *Research Journal of Chemical Sciences,* 2**,** 66-71.

Srirangan, K., Akawi, L., Moo-Young, M. & Chou, C. P. 2012. Towards sustainable production of clean energy carriers from biomass resources. *Applied energy,* 100**,** 172-186.

Stafford, W., Cohen, B., Pather-Elias, S., Von Blottnitz, H., Van Hille, R., Harrison, S. T. & Burton, S. G. 2013. Technologies for recovery of energy from wastewaters: Applicability and potential in South Africa. *Journal of Energy in Southern Africa,* 24**,** 00-00.

Stats, S. A. 2019. *Energy and the poor: a municipal breakdown* [Online]. Available: http://www.statssa.gov.za/?p=11181 [Accessed 12 March 2019].

Steffen, R., Szolar, O. & Braun, R. 1998. Feed Stock for anaerobic digestion making energy and solving modern waste problem. *Institute of Agrobiotechnology Tulin, University of Agricultural Sciences, Vienna, Australia*.

Steinmetz, R. L. R., Mezzari, M. P., Da Silva, M. L. B., Kunz, A., Do Amaral, A. C., Tápparo, D. C. & Soares, H. M. 2016. Enrichment and acclimation of an anaerobic mesophilic microorganism's inoculum for standardization of BMP assays. *Bioresource Technology,* 219**,** 21-28.

Stewart, D., Bogue, M. & Badger, D. 1984. Biogas production from crops and organic wastes. 2. Results of continuous digestion tests. *New Zealand journal of science,* 27**,** 285-294.

Surendra, K., Takara, D., Hashimoto, A. G. & Khanal, S. K. 2014. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews,* 31**,** 846-859.

Sutaryo, S. 2012. *Optimisation and inhibition of anaerobic digestion of livestock manure.* Aarhus UniversitetAarhus University, Science and TechnologyScience and Technology, . Aarhause, Denmark.

Syaichurrozi, I. 2018. Biogas production from co-digestion Salvinia molesta and rice straw and kinetics. *Renewable Energy,* 115**,** 76-86.

Syaichurrozi, I., Rusdi, R., Hidayat, T. & Bustomi, A. 2016. Kinetics Studies Impact of Initial pH and Addition of Yeast Saccharomyces cerevisiae on Biogas Production from Tofu Wastewater in Indonesia. *International Journal of Engineering-Transactions B: Applications,* 29**,** 1037.

Syaichurrozi, I. & Sumardiono, S. 2013. Predicting kinetic model of biogas production and biodegradability organic materials: biogas production from vinasse at variation of COD/N ratio. *Bioresource technology,* 149**,** 390-397.

Takashima, M., Shimada, K. & Speece, R. E. 2011. Minimum requirements for trace metals (iron, nickel, cobalt, and zinc) in thermophilic and mesophilic methane fermentation from glucose. *Water environment research,* 83**,** 339-346.

Tanimu, I., Mohd Ghazi, T., Razif Harun, M. & Idris, A. 2014. Effect of Carbon to Nitrogen Ratio of Food Waste on Biogas Methane Production in a Batch Mesophilic Anaerobic Digester. *International Journal of Innovation, Management and Technology,* 5**,** 116-119.

Tawona, N. 2015. *Valorisation Of Biowaste Via Production Of Biogas And Biofertilizer.* Master of Science in Engineering, University of KwaZulu-Natal. South Africa.

Tchobanoglous, G., Eliassen, R. & Theisen, H. 1977. *Solid Wastes: Engineering Principles and Management Issues*, McGraw-hill.

Tong, X., Smith, L. H. & Mccarty, P. L. 1990. Methane fermentation of selected lignocellulosic materials. *Biomass,* 21**,** 239-255.

Tuesorn, S., Wongwilaiwalin, S., Champreda, V., Leethochawalit, M., Nopharatana, A., Techkarnjanaruk, S. & Chaiprasert, P. 2013. Enhancement of biogas production from swine manure by a lignocellulolytic microbial consortium. *Bioresource technology,* 144**,** 579-586.

Turick, C. E., Peck, M. W., Chynoweth, D. P., Jerger, D. E., White, E. H., Zsuffa, L. & Kenney, W. A. 1991. Methane fermentation of woody biomass. *Bioresource technology,* 37**,** 141-147.

Tutuk, D. K. 2011. Biogas production from cassava starch effluent using microalgae as biostabilisator. *International Journal of Science and Engineering,* 2**,** 4-8.

Twidell, J. & Weir, T. 2015. *Renewable energy resources*, Taylor & Francis. London and New York

Uchechukwu-Agua, A. D., Caleb, O. J. & Opara, U. L. 2015. Postharvest handling and storage of fresh cassava root and products: a review. *Food and Bioprocess Technology,* 8**,** 729-748.

Umeghalu, C., Chukwuma, E., Okonkwo, I. & Umeh, S. 2012. Potentials for biogas production in Anambra State of Nigeria using cow dung and poultry droppings. *International Journal of Veterinary Science,* 1**,** 26-30.

Van Foreest, F. 2012. *Perspectives for biogas in Europe*, Oxford Institute for Energy Studies Oxford, United Kingdom.

Van Zyl, W. H., Chimphango, A., Den Haan, R., Görgens, J. & Chirwa, P. 2011. Next-generation cellulosic ethanol technologies and their contribution to a sustainable Africa. *Interface Focus,* 1**,** 196-211.

Verma, V., Singh, Y. & Rai, J. 2007. Biogas production from plant biomass used for phytoremediation of industrial wastes. *Bioresource technology,* 98**,** 1664-1669.

Wang, W. Cassava production for industrial utilization in China–present and future perspective. Cassava research and development in Asia: exploring new opportunities for an ancient crop. seventh regional cassava workshop, Bangkok, Thailand, 2002. 33-8.

Wang, X., Yang, G., Feng, Y., Ren, G. & Han, X. 2012. Optimizing feeding composition and carbon–nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresource Technology,* 120**,** 78-83.

Wang, Y., Li, G., Chi, M., Sun, Y., Zhang, J., Jiang, S. & Cui, Z. 2018. Effects of co-digestion of cucumber residues to corn stover and pig manure ratio on methane production in solid state anaerobic digestion. *Bioresource technology,* 250**,** 328-336.

Wantanee, A. & Sureelak, R. 2004. Laboratory scale experiments for biogas production from cassava tubers. *Asian Journal on Energy and Environment Research,* 8**,** 444-453.

Wei, S., Zhang, H., Cai, X., Xu, J., Fang, J. & Liu, H. 2014. Psychrophilic anaerobic co-digestion of highland barley straw with two animal manures at high altitude for enhancing biogas production. *Energy Conversion and Management,* 88**,** 40-48.

Weiland, P. 2003. Production and energetic use of biogas from energy crops and wastes in Germany. *Applied biochemistry and biotechnology,* 109**,** 263-274.

Weiland, P. 2010. Biogas production: current state and perspectives. *Applied microbiology and biotechnology,* 85**,** 849-860.

Wessels, K. J., Colgan, M., Erasmus, B. F. N., Asner, G., Twine, W., Mathieu, R., Van Aardt, J., Fisher, J. & Smit, I. 2013. Unsustainable fuelwood extraction from South African savannas. *Environmental Research Letters,* 8**,** 014007.

White, J. 2011. *Biogas generation potential of coconut copra in the anaerobic digestion process.* Master of Engineering, University of Canterbury. Christchurch, New Zealand.

Whiting, S., Reeves, R. D., Richards, D., Johnson, M. S., Cooke, J. A., Malaisse, F., Paton, A., Smith, J. a. C., Angle, J. S. & Chaney, R. L. 2004. Research priorities for conservation of metallophyte biodiversity and their potential for restoration and site remediation. *Restoration Ecology,* 12**,** 106-116.

Winchester, N. & Reilly, J. M. 2015. The feasibility, costs, and environmental implications of large-scale biomass energy. *Energy Economics,* 51**,** 188-203.

Winkler, H. 2005. Renewable energy policy in South Africa: policy options for renewable electricity. *Energy Policy,* 33**,** 27-38.

Wu, Q., Maslyuk, S. & Clulow, V. 2012. Energy Consumption Inequality and Human Development. *Energy Efficiency-A Bridge to Low Carbon Economy***,** 101-116.

Wu, X., Yao, W. & Zhu, J. 2010. Biogas and CH4 productivity by co-digesting swine manure with three crop residues as an external carbon source. 2010 Pittsburgh, Pennsylvania, June 20-June 23, 2010, 2010. American Society of Agricultural and Biological Engineers, 1.

Yang, L. & Li, Y. 2014. Anaerobic digestion of giant reed for methane production. *Bioresource technology,* 171**,** 233-239.

Ye, J., Li, D., Sun, Y., Wang, G., Yuan, Z., Zhen, F. & Wang, Y. 2013. Improved biogas production from rice straw by co-digestion with kitchen waste and pig manure. *Waste management,* 33**,** 2653-2658.

Yenigün, O. & Demirel, B. 2013. Ammonia inhibition in anaerobic digestion: a review. *Process Biochemistry,* 48**,** 901-911.

Yohaness, M. 2010. *Biogas potential from cow manure–Influence of diet* Master thesis Swedish University of Agricultural Sciences. Uppsala, Sweden.

Zamanzadeh, M., Hagen, L. H., Svensson, K., Linjordet, R. & Horn, S. J. 2017. Biogas production from food waste via co-digestion and digestion- effects on performance and microbial ecology. *Scientific Reports,* 7**,** 17664.

Zema, D. A., Zappia, G., Benalia, S., Zimbalatti, G., Perri, E., Urso, E., Tamburino, V. & Bernardi, B. 2018. Limiting factors for anaerobic digestion of olive mill wastewater blends under mesophilic and thermophilic conditions. *Journal of Agricultural Engineering,* 49.

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

Zhang, P. 2012. *Biogas-Its Potential As An Energy Source In Rural Households With Particular Emphasis On China.* MSc, Norwegian University of Life Science. Norway.

Zhen, G., Lu, X., Kobayashi, T., Li, Y.-Y., Xu, K. & Zhao, Y. 2015. Mesophilic anaerobic co-digestion of waste activated sludge and Egeria densa: performance assessment and kinetic analysis. *Applied energy,* 148**,** 78-86.

Zhu, J., Zheng, Y., Xu, F. & Li, Y. 2014. Solid-state anaerobic co-digestion of hay and soybean processing waste for biogas production. *Bioresource technology,* 154**,** 240-247.

Zinder, S. H. & Koch, M. 1984. Non-aceticlastic methanogenesis from acetate: acetate oxidation by a thermophilic syntrophic coculture. *Archives of Microbiology,* 138**,** 263-272.

Züttel, A., Borgschulte, A. & Schlapbach, L. 2011. Hydrogen as a future energy carrier. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 368**,** 3329-3342.

APPENDICES

(Conference and Journal Publications)

APPENDIX P1

Journal Publication: An overview of biogas production: fundamentals, applications and future research (Literature Review) *[Accepted and Published]*

IJEEP

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2019, 9(2), 105-116.

An Overview of Biogas Production: Fundamentals, Applications and Future Research

Nathaniel Sawyerr[1]*, Cristina Trois[1], Tilahun Workneh[2], Vincent Okudoh[3]

[1]Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa, [2]Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu - Natal, Pietermaritzburg, South Africa, [3]Department of Biotechnology and Consumer Sciences, Cape Peninsula University of Technology, Cape Town Campus, South Africa.
*Email: sawyerrnathaniel@gmail.com

Received: 12 November 2018 **Accepted:** 07 February 2019 **DOI:** https://doi.org/10.32479/ijeep.7375

ABSTRACT

Due to the increase in population, both developed and developing countries are facing mainly issues surrounding the future energy security and a better use of natural resources. Such present and future energy problems can be solved by the use of renewable energy sources. Among several renewable energy sources is a sustainable means of anaerobic digestion (AD) for production of gases. In the past, AD as a source of biogas was used mainly for degradation of waste materials or toxic compounds. However, recently, there has been great interest in producing biogas from energy crops. This paper presents an overview of state-of-the-art and future viewpoints related to the AD process for biogas production.

Keywords: Biogas, Biomass, Anaerobic Digestion, Methane, Renewable Energy
JEL Classifications: Q4, P28

APPENDIX P2

Journal Publication: Identification and characterization of Potential Feedstock for Biogas Production *[Accepted and Published]*

JEE Journal of Ecological Engineering
Volume 20, Issue 6, June 2019, pages 103–116
https://doi.org/10.12911/22998993/108652

Received: 2019.03.16
Revised: 2019.04.19
Accepted: 2019.05.06
Available online: 2019.05.20

Identification and Characterization of Potential Feedstock for Biogas Production in South Africa

Nathaniel Sawyerr[1*], Cristina Trois[1], Tilahun Workneh[2]

[1] Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

[2] Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

* Corresponding author's e-mail: sawyerrnathaniel@gmail.com

ABSTRACT

Biogas is produced during anaerobic digestion (AD) of biodegradable organic materials and is considered a promising renewable energy resource. Feedstocks are essential to ensure the successful anaerobic digestion in biogas digesters. Therefore, the search of appropriate substrates has come into focus. In this study, we examined the potential substrates that could be used as feedstock for the successful operation of an anaerobic digester. The approach used in this study was to identify the potential feedstocks that can be converted into value-added products. The identification of the feedstocks was done based on classification and evaluation of the theoretical biogas and methane production during the digestion process. The results show that all the considered substrates exhibited the biogas theoretical yield, with cattle manure producing the highest yield (0.999 m^3/kg VS), whereas the lowest biogas yield (0.949 m^3/kg VS) was obtained from cassava peels. It was concluded that the use of cassava co-digested with fruit and vegetable waste as an alternative feedstock offers a greater potential in terms of biogas production and could thus be implemented in the biogas projects running with cow dungs inside South Africa, especially in rural communities.

Keywords: Cassava, fruit and vegetable, anaerobic co-digestion, biogas, methane theoretical production

INTRODUCTION

The clamour for the reduction of GHGs and the need for sustainable energy and environment has increased the research efforts into alternative fuels from renewable energy sources, including the bioresources (Achinas et al., 2017). Studies have suggested that in order to ensure the sus-

Political instability of the regions with commercially abundant oil and gas may translate to the insecurity of energy supply in many countries that import these products. Since human and animal wastes are available in every part of the world, biogas (extracted from biomass) will play a critical role for the future in energy (Achinas et al., 2017). Biogas, which is produced through anaer-

APPENDIX P3

Conference: Co-digestion of animal manure and cassava peel for biogas production in South Africa *[Accepted and Presented]*

9th Int'l Conference on Advances in Science, Engineering, Technology & Waste Management (ASETWM-17) Nov. 27-28, 2017 Parys, South Africa

Co-Digestion of Animal Manure and Cassava Peel for Biogas Production in South Africa

Nathaniel Sawyerr, Cristina Trois, Tilahun Workneh and Vincent Okudoh

Abstract**—** Global energy demand is on the rise due to continuous increases in population, economic growth, and energy usage. Several studies have been done on biogas, but in South Africa, these are biased towards industrial wastewater. Therefore, there is need to explore other alternatives for biogas generation, for example energy crops such as fodder beets and cassava, on which studies are limited. Cassava has several advantages compared to other crops, including the ability to grow on degraded land and where soil fertility is low. It also has the highest yield of carbohydrate per hectare (4.742 kg/carb) apart from sugarcane and sugar beet, which makes it suitable for bioenergy (biogas) generation. This study was designed to determine the performance of co-digestion of cassava peel (CP) with cattle manure (CM) at different ratios, as well as to study the effect of the mixed ratios on methane yield through batch anaerobic digestion. All digesters were run simultaneously under mesophilic temperatures of 35 ± 1 °C. The digestion was carried out in 600 mL SCHOTT DURAN® glass laboratory bottles. The results showed that co-digestion influenced biogas production and methane yield. The final cumulative methane yields by the co-digestion of CM and CP at the CM:CP mixing ratios of 80:20 and 20:80 were 738.76 mL and 838.70 mL, respectively. The corresponding average daily methane yields were 18.42 mL/day and 20.97 mL/day. This indicates that CP enhanced the production of methane in the co-digestion process with the 20:80 CM:CP ratio.

Keywords**—**Cassava, Biogas, Co-digestion, Biomass, Animal Manure.

quality and quantity of methane yielded and biogas produced largely depends on feedstock characteristics and digester operating conditions including hydraulic retention time, pH, carbon-nitrogen (C/N) ratio, and inoculum [2].

Therefore, improving the efficiency of biogas production also requires improving the characteristics of the feedstock and operating conditions of the digester.It is also well established that the co-digestion of two or more feedstocks produces a higher methane yield than a single feedstock [6, 7]. Co-digestion is the process of mixing two or more substrates and digesting them simultaneously. Some of the major benefits of anaerobic co-digestion over mono-digestion include increased biogas production and methane concentration [8, 9].

Co-digestion has been utilised extensively to improve the efficiency of biogas production. Its efficiency may be influenced by parameters such as nutrients, feedstock pH, temperature, feed flow rate (loading rate), feedstock type, mixture ratio, and retention time. However, these factors may slow or stall the process of biogas production if their values are not within a certain range. Therefore, understanding the importance and optimal operating conditions for each parameter during anaerobic digestion (AD) will contribute to the realization of optimal hydrolyses and digestion [10].

The function of co-digestion during AD includes balancing nutrients (C/N ratio, micro- and macro-nutrients), pH

APPENDIX P4

Journal Publication: Comparison and Kinetic Modelling of Biogas Production from unpeeled and peeled cassava Tubers at a Mesophilic Temperature

[Accepted and Published]

International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 12, December 2018, pp. 338–352, Article ID: IJMET_09_12_038
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=9&IType=12
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

COMPARISON AND MODELLING OF BIOGAS PRODUCTION FROM UNPEELED AND PEELED CASSAVA TUBERS AT A MESOPHILIC TEMPERATURE

Nathaniel Sawyerr, Cristina Trois
Department of Civil Engineering, College of Agriculture, Engineering and Science,
School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

Tilahun Workneh
Department of Agricultural Engineering, College of Agriculture, Engineering and Science,
School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

Vincent Okudoh
Department of Biotechnology and Consumer Sciences,
Cape Peninsula University of Technology, Cape Town Campus, South Africa

ABSTRACT

The production of energy from biomass such as an energy crop is gaining momentum due to the steady increase of the world population, economic growth and the accelerating cost of fossil fuels. In recent years, progressive climate change related to global warming and rampant Green House Gases emissions necessitates applied research in renewable energy generation from different sources. The purpose of this study, therefore, was to evaluate the potential of production of biogas from unpeeled and peeled cassava tubers at a mesophilic temperature of 37 °C in a 50-litre laboratory scale biogas digester, with cow dung (inoculum) as source of methanogens. The experimental design consists of two biomass raw materials (i.e. whole cassava and peeled whole cassava tuber). The highest biogas yield of 635.23 L/kg VS was obtained from peeled cassava tuber anaerobic fermentation using inoculum followed by the digestion of peeled cassava tuber as raw material without inoculum which led to the production of 493.35 L/kg VS. The feedstock of peeled cassava with inoculum, produced 28.75% more gas yield when compared to peeled cassava without inoculum. The Modified Gompertz model fitted the cumulative experimental methane gas data well. The model with the newly developed coefficients was used to predicate the maximum biogas yield at day 40. The validated results show that peeling the cassava tuber increase the biogas yield by 38% compared to the unpeeled tuber.

APPENDIX P5

Journal Publication: Optimization of Biogas Yield through co-digestion of Cassava Biomass and vegetable & Fruits waste at Mesophilic Temperature

[Accepted and published]

INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH
N. Sawyerr et al. ,Vol. 9, No. 2, June, 2019

Optimization of Biogas Yield through Co-digestion of Cassava Biomass, Vegetable and Fruits Waste at Mesophilic Temperatures

Nathaniel Sawyerr*‡, Cristina Trois**, Tilahun Workneh***

*,**Department of Civil Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu-Natal, Howard College, South Africa

*** Department of Agricultural Engineering, College of Agriculture, Engineering and Science, School of Engineering, University of KwaZulu- Natal, Pietermaritzburg, South Africa

‡Corresponding Author; First Author, Tel: +27 76 285 2310, sawyerrnathaniel@gmail.com

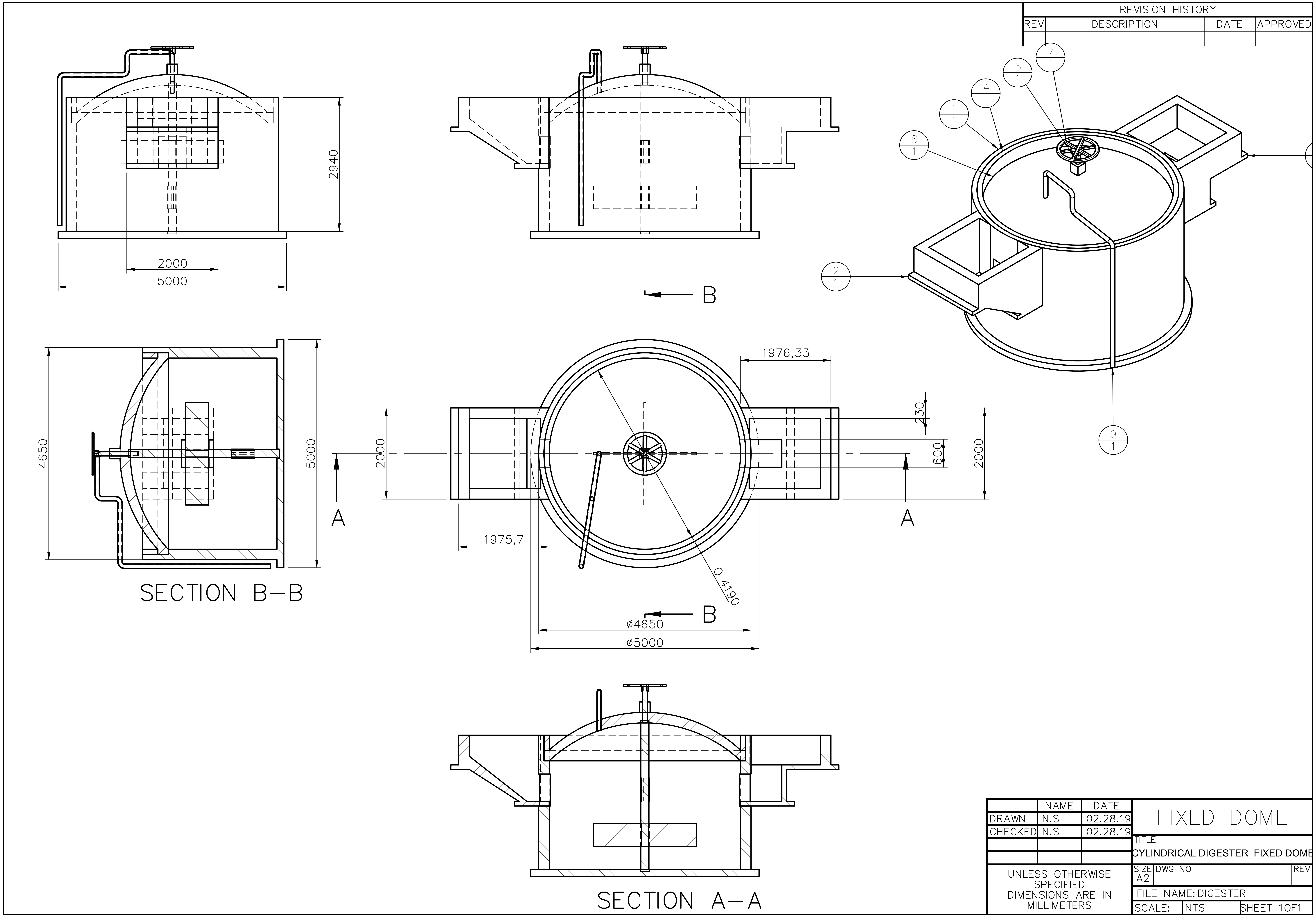
Received: 09.02.2019 Accepted:17.03.2019

Abstract- Biogas is a mixture of gases mainly methane and carbon dioxide, it is considered a clean and renewable form of alternative energy. It can be obtained through fermentation of any biomass in the absence of oxygen called anaerobic digestion. The objective of this paper is to obtain the optimum biogas yield through co-digestion of cassava biomass, vegetable and fruits at different ratios in a single stage fed-batch anaerobic digester for biogas production. The physical pre-treatment of the both substrates was by milling the feedstock into small pieces prior to anaerobic fermentation. Anaerobic digestion of the mix of cassava biomass and vegetable & fruit was investigated in a 600 ml digester for 31 days under mesophilic condition (37°C). Bio-methane potential of cassava biomass co-digested with vegetable & fruit ranged from 1124.26 to 1641.82 mL CH_4/g VS. Co-digestion of CB and V&F with inoculum at ratio of 40:60 achieved the maximum methane yield of 1641.82 mL/g VS which was 23.08% higher than that of the mono-digestion feedstock.

Keywords Anaerobic digestion; Gompertz model; Performance Index; Mon-digestion; Vegetable & Fruit.

APPENDIX D1

Drawing *[Construction]*


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
2000
5000
2940
4650
5000
SECTION B–B
B
B
A
A
2000
1975,7
1976,33
230
600
2000
Ø 4190
ø4650
ø5000
SECTION A–A
NAME
DATE
DRAWN
N.S
02.28.19
CHECKED
N.S
02.28.19
FIXED DOME
TITLE
CYLINDRICAL DIGESTER FIXED DOME
SIZE
A2
DWG NO
REV
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS
FILE NAME: DIGESTER
SCALE:
NTS
SHEET 1OF1