UNIVERSITY OF NAIROBI
FACULTY OF ENGINEERING
DEPARTMENT OF CIVIL AND CONSTRUCTION ENGINEERING.

BATCH ANAEROBIC DIGESTION OF BANANA PLANT RESIDUES FOR METHANE PRODUCTION

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F80/95467/2014

A project submitted in fulfilment of the requirement for the award of the degree Doctor of Philosophy in Civil Engineering of the University of Nairobi

JULY 2022

DECLARATION

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ACKNOWLEDGEMENT

First of all, I would like to my gratitude to my supervisors Dr. Zablon I. Oonge and Prof. Patts M. Odira for their supervision, guidance, and advice throughout the study period. I am equally pleased to acknowledge the assistance and guidance offered by the staff at the Institute for Sanitary Engineering and Waste Management, the Leibniz University of Hannover throughout the laboratory work. The great reserve of materials for this study made my work easier. Special thanks to MSc Seline Yueceer for all the insights you gave me about the laboratory work.

My gratitude to the Gandhi Smarak Nidhi Scholarship Fund for the scholarship that they offered me. The financial support offered me the opportunity to conduct my research and Broaden my knowledge.

These acknowledgements would not be complete without recognizing my friends who enriched my research through their comments and advice throughout this project. I could never have asked for better ideas and support than the ones you gave me.

This work would not have been possible without the support and continuous prayer and encouragement from parents and siblings. Last but not least, I would like to thank my family for the immeasurable encouragement and moral support, I dedicate this work to them.

To all of you, thank you and be blessed abundantly.

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°C	Degrees Celsius
BMP	Biochemical Methane Potential
BOD	Biochemical Oxygen Demand
CH_4	Methane
CHP	Combined Heat and Power
Cm	Centimetre
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
d	day
DIN	Deutsches Institut für Normung
g	Gram
GOK	Government of Kenya
GWH	Gigawatt hour
Ha	Hectare
HRT	Hydraulic Retention Time
IHK	Industrie und Handelskammer Nürnberg für Mittelfranken
JAICAF	Japan Association for International collaboration for Agriculture and forestry
KARI	Kenya Agricultural Research Institute
kg	Kilogram
kJ	Kilo Joule
Km	Kilometre
Km^2	Cubic Kilometre
kW	Kilowatt
kWh	Kilowatt-hour
L	Litre
Ltd	Limited
M	Meter

m^3	Cubic meter
Mg	Milligram
mL	Millilitre
MOA	Ministry of Agriculture Kenya
MSWM	Municipal solid waste management
MW	Megawatts
MWH	Megawatt hour
oDM	Organic dry matter
OLR	Organic Loading Rate
S-removal	Hydrogen Sulphide removal
t	Tons
TS	Total Solids
UASB	Upflow Anaerobic Sludge Blanket
UNEP	United Nations Environmental Program.
USAID	United States Agency for International Development
VDI	Verein Deutscher Ingenieure e.V

ABSTRACT

Agriculture is one of Kenyans' main economic activities and among the fruit grown is the banana. Kenya produces about one million tons of bananas yearly, of which the banana plant produces the fruits once in a lifetime and the rest of the banana plant parts are residues. The banana plant residues include leaves, stems and peduncles most of which are agricultural wastes. This study aims to establish the quantity and quality of methane gas produced from batch anaerobic digestion of banana plant residues. The leaf, stem and peduncle were the substrates used due to the ease of collecting them on the farm. The inoculum used was acclimatized sewage sludge from an anaerobic reactor in a wastewater treatment plant. Kinetic modelling was used to obtain the optimal kinetic parameters for the optimization of methane production. An anaerobic batch digestion test was conducted in triplicate batch systems, at a mesophilic temperature of (37°C) for 51 days. The biogas produced from the anaerobic digestion process was then subjected to gas chromatography to know the quality of the gas. The quality of biogas produced was of good quality and had a methane composition of 68%,65% and 69% for the stem, leaves and peduncle respectively and the methane yields were 0.125, 0.132 and 0.062 m^3CH4/kg oDM for the stem, peduncle, and leaf, respectively. The digestate pH at the end of the batch digestion was checked and was found to be 7.56,7.58,7.64 and 7.84 for the stem, leaf, peduncle, and seeding sludge respectively. From the results of the batch fermentation and gas chromatography, kinetic modelling was done for the methane yields using three models that is the First Order Kinetics, Logistic and Modified Gompertz models. To determine the model that best describes the degradation of complex substrates containing lignocellulosic materials and optimize the kinetic parameters and design parameters for an anaerobic digester. The Modified Gompertz model predicted data had the best fit with the experimental data as it had high R^2 values and low RMSE values for all the substrates. The values for R^2 were 0.992,0.974 and 0.994 for stem, leaf and peduncle respectively and the RMSE values were 2.293,2.382 and 2.342 for the stem, leaf and peduncle respectively. The predicted yields by the Modified Gompertz model were 0.123, 0.121 and 0.057 m^3 CH4 / kg oDM for the stem, peduncle and leaf, respectively. This study can be replicated on other agricultural and organic wastes to be used as feedstocks in the production of biogas and to promote anaerobic digestion technology as a source of clean and affordable energy.

CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND OF STUDY

Agricultural production has increased more than three times over the last fifty years because of the improved soils for agricultural use, improved technologies that lead to better production and the accelerated growth of the population, thus more food to feed the population (Mónica et al., 2020). The increased agriculture production has brought about increased agriculture plant residues which are solid wastes. These plant residues are organic and when not utilized and left to decompose, they have negative impacts on the environment and human health. These negative impacts majorly include the emission of greenhouse gases, harbouring of rodents and insects, leaking of leachates to the groundwater, and harbouring disease-causing vermin for example mosquitoes.

There are various ways of utilizing agricultural solid wastes to mitigate their negative impacts on the environment and human health. One way is through Anaerobic Digestion for Biogas production, since most agricultural wastes are organic. Anaerobic Digestion is one of the ways that address the global waste challenges and gears toward achieving some of the Sustainable Development Goals (SDGs) associated with waste management. The main SDGs that Anaerobic Digestion of Agricultural solid wastes addresses are SDG 7 ‘To Ensure access to affordable, reliable, sustainable and modern energy for all; SDG 8 ‘To Promote inclusive and sustainable economic growth, employment and decent work for all and SDG 13 ‘To Take urgent action to combat climate change and its impacts.

Anaerobic digestion of wastes produces amounts of methane that can be used as fuel and thus reducing reliance on traditional sources such as wood fuel and fossil fuel, thereby reducing greenhouse gas emissions since, as compared to other fuels fewer atmospheric pollutants and carbon dioxide are emitted per unit energy of methane.

In the rural areas of Kenya, whose population constitutes about two-thirds of the national population, the main source of energy is traditional biomass in the form of fuelwood and charcoal. This fact is a cause for concern given the depletion of forests and consequent environmental degradation arising from the cutting of trees for fuelwood and the burning of charcoal. Most of the people in the rural areas depend on agriculture as the main economic activity. To help reduce dependency on wood fuel, agricultural wastes could be used as a source of energy in the form of

biogas, biodiesel and bio-ethanol. Agricultural wastes are the residues left behind after harvesting the food part of the crop; they include, stalks, stems, roots, leaves, cobs, and straws. The common practice of handling these wastes is burning them before planting again new crops, feeding to livestock, or leaving them on the land to act as hummus with unstable carbon, thus, converting these wastes to biofuels will mitigate greenhouse gas emissions, encourage the use of digestate as hummus with stabilized carbon compounds and also promote good practices of sustainable agricultural waste management. Biogas is a beneficial way of utilizing biomass for energy needs, mostly for domestic lighting and heating. There are multiple benefits of a functioning biogas system which include environmental protection and resource conservation.

Banana occupies a distinctive place in Kenya's national as well as household economy. Its share of the total fruit area covered in Kenya is at 55% and occupies almost 7.5% of the gross cropped area. In several counties of Kenya, large proportions of the farmers grow and consume bananas as one of the staple foods. In 2019, bananas production in Kenya was 1.72 million tons. Bananas production in Kenya increased from 400,000 tons in 1970 to 1,720,000 tons in 2019 growing at an average annual rate of 6.97% (Knoema, 2020). The increase in banana production can be attributed to new technologies such as tissue culture and also the increased demand for the fruit with the population increase. This increase in production also reflects the increase of banana plant residues in the farms and thus the necessity to manage these wastes sustainably. After harvesting the banana fruit, the banana plant residues comprising the pseudo stem, peduncle, leaves, corms, rachis, and waste fruits are mainly fed to livestock or left on the farm to decompose to form organic fertilizer (hummus). The use of the banana residues in the farms as hummus with carbon compounds that are not stabilized leads to greenhouse gas emissions.

From various literature and studies, it is not so conclusive the amount of gas that can be produced by banana leaves, peduncles, and stems when used as substrates, since most of the studies have the banana plant residues mixed with other substrates. Therefore, there is a need to see how these banana plant residues degrade and also the amount and quality of biogas produced when used as substrates solely. If there is sufficient gas then this will help, most banana farmers access a renewable source of energy from a simple technology. Ultimately the banana plant residues will be properly managed to mitigate the negative impacts of greenhouse gas emissions.

The operations of anaerobic digesters have indicators that illustrate their performance these include process parameters (Volatile Fatty Acids, COD removal, pH) and Kinetic parameters (hydrolysis rate, lag phase and methane production potential). However, the performance of the anaerobic digester based on these parameters is not well understood, thus necessitating modelling of the anaerobic process. Mathematical modelling comes in as a tool to aid in understanding the complex process of conversion of organic substances to biogas and other gases through various bacteria groups. Modelling is also an easy tool to demonstrate various complex processes. There is a technical challenge when there is no concise process control and optimization, since toxic and harmful compounds may be produced causing low methane yield, reduced system stability, or foaming. In this study, the modelling was conducted to optimize the kinetic parameters for operations of the anaerobic digesters.

1.2 PROBLEM STATEMENT

Agriculture is one of the leading economic activities in Kenya with almost 75% of the population making their living from it. Most farmers other than growing cash crops, grow food crops for their consumption, among the food crops grown in Kenya are bananas. After harvest, most of the residues are left on the farm or fed to domestic animals (cattle, goats and sheep). Most large-scale banana farmers do not have cattle to be fed with these residues (leaves, stems and peduncles), thus managing these banana plant residues is an issue as most are left on the farm to act as hummus fertilizer with carbon compounds that are not stabilized, emitting greenhouse gases to the environment. In case of excess harvest, farmers opt to sell the products as there are no storage facilities on the farm. If perishable goods lack a quick market, they become waste since there is no energy to provide for refrigeration of most of the produce.

The lack of reliable, affordable, and readily available energy and the high cost of fuel and fertilizer coupled with the high rate of farm produce losses is a major economic problem for farmers in Kenya. Conversion of locally available by-products to these resources can greatly improve community development and welfare. The banana plant residues are such products that are organic and can be utilised for biogas production.

Kenya faces problems concerning both the commercial energy forms that have fuelled economic development and the traditional energy sources upon which most of the population still depends.

The traditional sources of fuel are not energy sufficient and produce harmful emissions, especially carbon monoxide. Over-reliance on biomass fuel especially wood has brought about the overuse of forest resources and negative environmental impacts. The forest cover has reduced and thus the reduction of the water catchment area with time. This has resulted in a reduction of water resources, such as river inflows, dried-up rivers, reduced rainfall and dam water levels reduction leading to less hydropower generation. The use of petroleum products for energy production is also not a sustainable solution because of the rampant variations in global crude oil prices and the negative impacts of greenhouse gas emissions. Embracing the use of biofuels of which the banana plant residues is part, will provide a solution to mitigate some of the environmental, health, and energy problems in Kenya especially the rural areas, and also attain benefits such as quality fertilizer for good farming practices. Moreover, good banana plant residue management would have been achieved.

The study uses the banana stems, leaves and peduncles as substrate as they are easy to collect and handle within the farm, it is also, easy to weigh these banana plant residues for purpose of estimating the anticipated quantity of biogas produced and thus evaluating the digester efficiency. Anaerobic digestion is a composite process involving four-step reactions whose ultimate product is biogas. Anaerobic digesters' operations are uncertain, not well understood and are controlled by various process and kinetic parameters. Mathematical modelling assists in providing an understanding of the complex process, design, optimization, prediction of process and Kinetic parameters and prediction of the performance of anaerobic digesters. Modelling has been conducted to optimize the operations of the anaerobic digesters and predict the kinetic parameters for the anaerobic digestion process.

1.3 GOAL AND OBJECTIVES OF THE STUDY

The main goal of this study is to compare the optimal Methane produced by the various banana residues(stem, peduncle, and leaves) from the anaerobic digestion process through kinetic modelling. This goal leads to proper agricultural solid waste management by use of a simple and affordable technology that will also enable the ability to get methane gas for use on the farm and minimise the use of agricultural residues that has unstable compounds for use as hummus. To attain the goal, this study comprises various objectives as follows:

i) Perform batch anaerobic digestion of the banana plant residues (stem, leaf and peduncle) as substrates at a mesophilic temperature to quantify the methane production from these substrates and establish the chemical suitability of digestate for use as fertilizer.
ii) Comparison of biogas and methane values obtained from the laboratory with calculated theoretical values using COD of the banana residues and establishing the relationship between theoretical and experimental values.
iii) Use of Kinetic Models to obtain the kinetic parameters and the suitable kinetic model to explain the process of anaerobic digestion of banana plant residues.
iv) To optimize the anaerobic digestion process by use of Kinetic modelling and also, use the models for quality control in the estimation of the ultimate methane yield and compare with what is obtained from the experiment for batch anaerobic digestion.

1.4 HYPOTHESES

The hypotheses for this research are as follows: -

i) A batch set up anaerobic digester under mesophilic conditions and with a suitable inoculum, is capable of digesting banana plant residues (leaf, stem, and peduncle), consisting of varying amounts of lignocellulosic materials, to produce substantial and quality biogas and a stabilized digestate.
ii) Models can be used to explain the theoretical background interpretation of the production rate of methane and the kinetics of anaerobic digestion.
iii) The exponential models best explain the kinetics of slowly degradable lignocellulosic substrates whereas Logistic models best explain the kinetics of rapidly degradable lignocellulosic substrates.

1.5 SCOPE OF STUDY

The thesis is developed as an integration of experimental research and mathematical modelling to achieve the optimization of the anaerobic digestion of the banana plant residues. The experiment phase was aimed at being able to see if the wastes are degradable and also if the final digestate is stabilized. The modelling is aimed at optimizing the anaerobic digestion process.

In chapter one there is an introduction to solid waste handling in farms and rural areas of Kenya. Here also there is an introduction to the energy sources mix used by the majority of Kenyans in

the rural areas where banana is farmed. Also, the main objectives and rationale of the research are stated here. The hypotheses for research are also stated in this chapter.

Chapter two has the literature review on the state of agricultural waste management in Kenya, various energy sources and biogas in Kenya, and banana farming in Kenya. The chapter also describes the anaerobic digestion technology in depth. In this chapter, the modelling of the Anaerobic digestion process is reviewed and the three mathematical models (First Order Kinetics modelling, Logistic and Modified Gompertz models) used are described in-depth and also why these models have been selected.

The methodology used to gain the data for research is fully described in chapter four. While chapter five uses the data from chapter four to form a decision based on the hypotheses for research. The results which are the data are discussed in depth in this chapter. The results are set in perspective by performing calculations on the data obtained from the experimental results. The results of this research are summarized and discussed using three ways of analysis that is, scientific achievement, methodological impacts, and societal consequences.

Finally, in chapter six the conclusions of the study are drawn and the research gap being bridged is also elaborated on in this chapter. Recommendations for further studies related to this research are also stated in this chapter.

1.6 LIMITATIONS OF THE STUDY

The study researched each substrate on its own, but considering a farm setup, if a biogas plant is to be set up it will be used for digesting all organic wastes available. Thus, the limitation here is the co-digestion of the various organic wastes with banana plant residues.

This experiment was conducted on a laboratory scale so, projecting it to the field scale was done by modelling on assumptions that most conditions are the same in the field and as in the laboratory but in reality, this is not the case. Various areas have various optimal operating conditions that influence the choice of an economically viable digester.

Banana plant residues are highly organic and also have high moisture content if not stored properly most of its gas content might be lost, and also bad smells may be emitted into the atmosphere, atmosphere, and insects and scavengers may be attracted to the waste, so good storage is required. To deal with this, the best storage methods must be devised to reduce the moisture before digestion. Sun-drying or ensiling of the waste before digestion is one of the appropriate ways to prepare the waste for digestion and also storing. This study does not consider the storage of wastes as it awaits digestion, considering its batch digestion and the retention time for the wastes in the digester is more than fifty days.

CHAPTER 2

2. LITERATURE REVIEW

2.1 BACKGROUND INFORMATION

2.1.1 Solid Wastes Management in Kenya

Solid Waste Management (SWM) is a cross-cutting issue that impacts and touches on various aspects of sustainable development including the ecology, economy and society. According to (Ljiljana & David, 2017) areas affected by Solid waste management systems include sanitation, living conditions, terrestrial ecosystems, marine ecosystems, public health, access to decent jobs and the sustainable use of natural resources. Solid Waste Management involves the collection, transporting, resource recovery, recycling, and treatment of wastes. The main objective of SWM is to protect environmental quality, develop sustainability, promote good health for the population and provide support to economic productivity. To meet these goals, sustainable solid waste management systems must be observed and adopted by the communities and also public and private sectors.

In Kenya, local authorities are charged with the responsibility of collecting and disposing of solid and liquid municipal wastes within their areas of jurisdiction. Centralized SWM systems are used by most local authorities in Kenya. Solid waste management is mainly concentrated in urban areas; in suburban and rural areas residents have to individually come up with ways of handling their waste. The common practice is to burn most of the wastes in the compound, compost the organic wastes or dispose of them off to pit latrines. The bulk of waste in most rural areas of Kenya is agricultural and food wastes; most of this is composted in individuals' compounds. There is nothing much done to the compost, thus mostly releases bad odours to the surroundings and the leachate is released to the ground. According to Mónica et al. (2020), the future projections show high growth in agricultural production, this means increased solid waste from agriculture both globally and locally (Kazimierczuk A., 2019).

Agriculture wastes currently are being used as hummus fertilizer and animal fodder the remaining wastes are majorly burnt in the fields or used as biomass. The burning of agricultural ways leads to loss of organic matter, environmental pollution, human health problems and greenhouse gas emissions. Agriculture wastes are one of the main sources of anthropogenic methane to the

atmosphere and anaerobic digestion can be utilized to convert these wastes into biogas a renewable source of energy, reducing methane emissions by almost 50% and the solid residue can be used as fertilizer rich in nutrients and with stable carbon compounds. According to Merlin and Boileau (2013), the lack of understanding in anaerobic digesters operations has resulted in numerous failures and thus the knowledge of anaerobic digestion limitations, reasons for failures, design and engineering deficiencies, complex digestion processes and appropriate equipment is important. Generally, there is no standard designed digester since the operating conditions are diverse and there are many incomplete research problems on metabolic pathways, microbial ecology, metabolic pathway, microbiology and modelling anaerobic digestion technologies.

To utilize the Agricultural wastes fully as we progress toward a circular economy there are three important elements in the advancement of Anaerobic digestion of agricultural wastes include;

(i) Establishment of circular centres for use of agricultural wastes.
(ii) Development of optimization strategies for an Anaerobic Digestion system, including substrate pre-treatment, and system configuration and control.
(iii) Maximizing of economic benefits of digestate uses.

The understanding of all processes of anaerobic digestion of particular substrates is thus an important aspect in trying to realise substantive yields of Biogas and thus the need to model this process.

2.1.2 Energy Situation in Kenya

Sustainable energy systems are required to mitigate climate change. The main factors that shape a sustainable energy supply are economic development, technological innovation, and policies in place. According to (Kazimierczuk A., 2019) most countries have committed to work towards achieving clean energy to meet the Sustainable Development Goals (SDG) agenda regarding SDG 7 (energy and energy access) and SDG 13 (climate change), and also the commitments made during the Twenty-First Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, 2015.

In Kenya, the total installed energy capacity as of the year 2017 was 2333 MW. Electricity accessibility is at 55% of the population, which is an improvement as compared to in 2013 when

27% of the population had access. Approximately 75% of the generated electricity is from renewable sources geothermal and hydro. The rest comes from thermal plants that use fossil fuels. Kazimierczuk A. (2019) noted there is diversification in the use of other renewable sources to generate electricity such as the use of wind power and solar power. More studies and focus can also be diverted on energy from waste.

According to Njiru & Latema (2018), in Kenya charcoal, cow dung, firewood and agricultural residues like maize and sorghum stalks are the common fuel sources. Over 80% of the urban dwellers use charcoal, the rural population rely on biomass mainly as fuel. Biomass, specifically wood, is by far the most widely used renewable fuel, this excessive demand for wood fuel continues to lead to deforestation, forest fragmentation, and land degradation, and threatens water catchments. Liquefied petroleum gas (LPG) is also a major form of fuel used in Kenyan homesteads since it is readily available and also the Government of Kenya's strategies to subsidize its cost.

Kenya faces problems concerning both the commercial energy forms that have fuelled economic development and the traditional energy sources upon which most of the population still depends. The traditional sources of fuel are not energy efficient and emit harmful emissions, especially carbon monoxide which has led to many deaths in both rural and urban areas. Reliance on wood fuel has reduced the forest cover, which acts as the water catchment area. As a result, reduced amount of natural water resources, rivers have decreased in size or even dried up, reduced rainfall and dam water levels have gone down leading to less hydropower generation, thus, inconsistent power supply and frequent power outages. Kenya depends mostly on hydropower and geothermal power; this calls for the exploitation of other sources of power to supplement it. The cost of fossil fuel is on the rise and it’s also becoming scarce with time.

As the population increases so does the energy demand, thus, in response to this increase in demand for energy the government must get innovative strategies to diversify and create more energy sources that are sustainable environmentally and economically and also efficient. The use of biogas will enhance energy efficiencies in rural populations.

2.2 THE BANANA PLANT

Bananas are the fourth in the global food commodity consumption after wheat, rice and maize. It is produced in over 100 countries, on an approximate area of 10.000,000 ha, and an annual harvest of 88 million tons (Tesfa & Mekias, 2015). The banana fruits throughout the year make it to be consumed all year round, thus it is not a seasonal fruit. Other than being a food crop it is also and source of income for the farmers. Eastern and Southern Africa produce about 20,000,000 tons of the world's production of bananas.

2.2.1 Banana plant parts

The banana plant is a perennial, large, monocotyledonous herb 2–9 m in height that arises from large, corms. The corm is an underground rhizome having buds, from which rhizomes grow to produce suckers. The banana plant has many fibrous and adventurous roots spreading laterally and forming a dense mat. The pseudo stem supports a canopy consisting of more than six leaves having overlapping leaf sheaths which are tightly rolled around each other to form a rigid bundle. New leaves originating from the corm emanate continuously from the pseudo stem centre. The leaves come out as large, long blades with a midrib and parallel veins.

The peduncle extends from the centre of the stem and buds and has flowers arranged in several groups. The true stem emerges from the centre of the tightly rolled bunch of leaves on flowering. The elongated bud is a cluster of odd-looking female flowers whose ovaries ripen into fruit. Each flower cluster which has about 12-20 flowers is distinct on the peduncle. The fruit and flowering parts are the bunches, the hands are single clusters of fruits, and a finger is an individual fruit (Nelson et al., 2006).

2.3 BANANAS IN KENYA

Most Kenyans obtain their food, livelihoods, employment, and foreign exchange earnings from the agricultural sector. Small-scale farmers make up 80% of the farmers in the country; producing 50% of the marketable output. The low-level use of farm inputs amongst the farmers has often resulted in sub-optimal levels of production (Matere et al., 2010). The banana is an important horticultural crop in Kenya due to its contribution to food security and income for small-scale land owners. The continuity of year-round production of bananas contributes majorly to the food and income security of banana growers. 2% of Kenya’s land used for crop production which is

approximately 80 000 hectares is under banana farming by small-scale farmers, who have an average banana holding of 0.3ha.

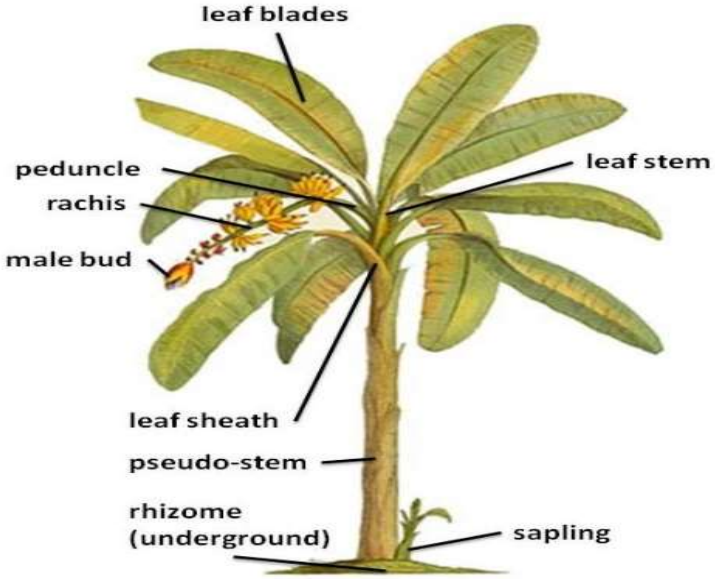

Figure 2.1: Banana Morphology

Banana is grown in various agro-ecological zones in Kenya, from the coast up to an altitude of about 2000m in the Western Highlands. Cultivation takes place under rainfed conditions in areas that receive an annual rainfall of at least 1000mm. Bananas are grown in most parts of Kenya and the seven major growing counties are Meru, Tharaka Nithi, Embu, Kirinyaga, Muwanga, Kasi and Nyamira. In 2019 the banana production was 1.4 million tons.

Banana yields are affected by pests which cause almost 50% loss of the produce. The other major setback in banana farming is that there is a lack of storage of the harvest at the farm and due to its perishable nature, there is a lot of wastage of the harvest. It is estimated that there are 25% to 30% losses in banana produce yearly. Banana processing is not so much exploited in Kenya, but a few companies have ventured into it. Most of the big companies that are processing bananas such as Delmont Kenya Ltd, Premier foods Ltd, and Bio Foods Kenya, produce juices, canned bananas, yoghurts, jams and banana crisps. The waste from these factories is locally disposed of and is mainly by composting or feeding livestock in the neighbouring villages. Small companies based in rural areas are also emerging due to the introduction of tissue culture banana farming in Kenya which ensures a year-round supply of sufficient bananas for processing. These small companies

such as Nyangorora Youth Group company produce banana flour for making bread, cakes and biscuits, also, they use ripened bananas to make wine, jam, juice, beer, yoghurt, cakes and doughnuts. The banana plant residues are used to make ropes, mats and caps, but most of it is thrown on the open dumpsite.

2.3.1 Banana cultivation in Kenya

Banana cultivation is done through clonal propagation; by using healthy suckers of about 1.5 m high and 45 cm girth and spaced at 3 by 3 m. For Bananas to give maximum yield, several factors are considered important. They include:

i) Soil type - bananas grow in diverse types of soils, but ideally require a deep, well-drained loam soil with high humus content, which allows good root growth.
ii) Nutrient Intake- bananas take a considerable amount of nutrients, especially potassium; those removed in harvested fruits, must be replaced if continuous production of the plantation has to be maintained.
iii) Soil Management -these are techniques done to restore or add soil nutrients to the soil and mulching is one of the ways and is preferred since it suppresses the weeds, conserves the moisture, and maintains the soil fertility.

Soil fertility involves the biological, physical, and chemical components of the soil and encompasses management practices within a cropping system. Soil nutrient levels in banana fields are often sufficient due to:

i) Loss of nutrients from banana fields is less.
ii) There is an addition of nutrients to the farm before banana farming, especially by mulching.
iii) Fertile fields are required for banana production.

2.3.2 Marketing channels for bananas in Kenya

Bananas in Kenya are sold unripe immediately after harvest by the farmer. Thus, there is minimal post-harvest handling. The banana at the farm is sold as a whole bunch with the peduncle. The marketing channels for bananas in Kenya are shown in Figure 2.2.

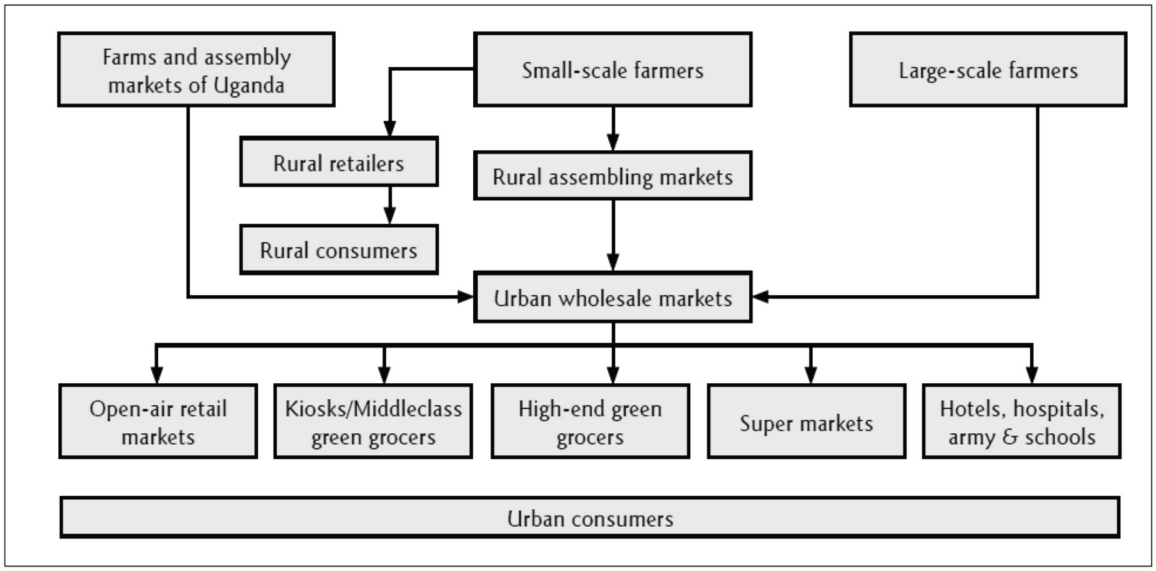

Figure 2.2: Marketing channels for bananas in Kenya (Acharya & Mackey, 2008)

Four main marketing channels carry bananas from the farm gate to the ultimate consumer:

i) A simple channel in which banana moves from a small farm to rural retailers and ultimately to the rural consumer.
ii) Produce goes to a village or other assembler and then to the wholesale market for onward transmission to urban retailers.
iii) Produce from a relatively large-scale producer goes directly to wholesale markets and then to the retailers in the urban areas.

The bananas are imported (from Uganda or Tanzania). From the wholesale market, the bananas go to the consumer through open-air retail markets, kiosks, high-end greengrocers, or supermarkets. (Africa Harvest Biotech Foundation International, 2008). Bananas in Kenya are sold unripe immediately after harvest by the farmer. Thus, there is minimal post-harvest handling. The banana at the farm is sold as a whole bunch with the peduncle. Four main marketing channels carry bananas from the farm gate to the ultimate consumer:

i) A simple channel in which banana moves from a small farm to rural retailers and ultimately to the rural consumer.
ii) Produce goes to a village or other assembler and then to the wholesale market for onward transmission to urban retailers.

iii) Produce from a relatively large-scale producer goes directly to wholesale markets and then to the retailers in the urban areas.

iv) The bananas are imported (from Uganda or Tanzania). From the wholesale market, the bananas go to the consumer through open-air retail markets, kiosks, high-end greengrocers, or supermarkets (Africa Harvest Biotech Foundation International, 2008).

2.3.4 Banana transportation in Kenya

In banana marketing, transportation is a major cost because banana is a bulk commodity and requires careful handling owing to their perishable nature (Africa Harvest Biotech Foundation International, 2008). Banana is produced in rural areas by small-scale farmers and is normally collected by a broker or brought by the farmer to a collection centre by the roadside. Farmers use a bicycle, motorbikes, human pottage, donkeys, or wheelbarrows as shown in Figure 2.3. The brokers mainly use pickups or handcarts to collect the bananas from the farms. To protect the fruit and maintain its quality during transportation the banana fruit is covered with banana leaves. From the collection centres where the bananas are bought in wholesale terms, they are collected in big lorries and taken to the urban centre markets, where the product is sold to the retail market which it then sells to the consumers. From the collection centres where the bananas are bought in wholesale terms, they are collected in big lorries and taken to the urban centre markets, where the product is sold to the retail market which is then sold to the consumers.

Figure 2.3: Various mode of transporting bananas to the market from the farm, on the right is the use of a bicycle while on the left is one form of human pottage.

2.3.5 Material, Energy Recovery and Disposal of Banana plant residues in Kenya

Due to limited resources and limited space for agricultural land, priorities for their utilization have to be set. These priorities will be defined by the number of alternative sources available. Food depends on agricultural land, there is no alternative for food production other than to use this land for growing crops. Plant growth only for material production (e.g. cotton) appears to be inevitable, but fossil or artificial resources serve many purposes just as well. For energy production, it is least reasonable to cultivate crops, since there are plenty of other possibilities (e.g. wind power stations, solar energy, hydroelectric plants, and Geothermal). This leads to the order of priority shown in Figure 2.4, food production, material production, and at last energy production.

Figure 2.4: Hierarchy of utilization for banana production

With the banana plant, it is possible to unite all these three uses at once. While the banana fruits serve as food, still several parts can serve as usable material, such as for woven baskets, as fertilizer, or as parts of composite materials. Even if the material uses of the banana plants made no economic sense, all plant parts can still serve for the production of biogas and thus energy, as the results of this study confirm. For this reason, the material uses and non-usable parts for disposal will be described in greater detail. Only the banana fruits and the male bud are used as food in Kenya. The main way to minimize solid waste and its negative effects is to utilize all the useful components, after which the rest can be disposed of if not economically utilizable. Banana plant residues usually comprise the leaves, spoilt fruits, peels, pseudo stems, leaf sheath, peduncle, and the rachis. Up to date, only a small amount of banana plant residues has been used as a material source, although a large variety of possible uses exist as follows: -

Leaves

Banana leaves have approximately 85% water and about 15% protein (Okoleh et al., 2015). The removal of the fully expanded lower banana leaves up to 12 times during the plant lifespan does not affect fruit yield. This implies that banana leaves can be used throughout the year. In Kenya the leaves are used in the following ways:

i) *Vermicomposting* -This is the processing of organic wastes using earthworms. Earthworms ingest and transform organic residues into high-quality humic material. The composting bed is mostly covered by banana leaves (Savala, 2003.)

ii) *Animal feed* - Banana leaves are an important source of fibre and are used as livestock feed (Reynolds, 1995). Banana leaves do not meet animal feed nutrient requirements and are often supplemented with other feeds or supplements containing nitrogen and carbohydrates (Mohapatra et al., 2010). The study by Kimambo & Muya (1991) established that banana leaves, banana peelings and the stem core provide sufficient and high nutritional value food for dairy cows and cattle. The banana leaf is cherished by animals as dry season feed. The people from the Mount Kenya region have been using banana leaves as animal feed for a long time especially for feeding their dairy cattle, whenever there is a drought. Cattle fed on banana leaves and stems need less water as parts of the plant to contain a lot of water (Ekwe et al., 2011).

iii) *Food preparation* - In cooking and food preparation and storage, banana leaves are used for lining cooking pots, wrapping food for cooking, storage and keeping it warm. After these usages the leaves become waste.

iv) *Cultural uses* - Traditional dancers usually use leaves to make dancing costumes. Also, during ceremonies leaves were put on the path leading to the function area and also on the vehicles transporting people there. Putting banana plants with their leaves on the path and entrance is welcoming and a respectful gesture during social functions especially weddings. After the ceremony and also the dancing the leaves become waste.

v) *Lining and Protection* - Leaves are used mostly when handling bananas in transit, they are lined on vehicles before the bananas are put to protect the fruit and maintain quality. The leaves are also used to cover the bananas while on transit as a shelter from harsh weather conditions and dust while on transport. Also, in the rural markets, the leaves are used to line the ground where the fruits or wares on sale are placed. The banana bunch is also protected from predators such as birds by covering it with banana leaves.

vi) *Mulching* - Mulching is a traditional practice preferred for its conservation of moisture, maintenance of soil fertility and suppression of weeds. This is done by spreading plant residues (banana leaves included) after harvest, on the farm.

vii) *Art and Craft* - Banana leaves in Kenya have been used as a raw material in various pieces of art and craft which include photo frames, hats, table mats, earrings, ropes, baskets, table mats, handbags, mosaics, collages and even batiks as shown in Figure 2.5.

viii) *Thatching/ Roofing* -In the rural areas where banana is grown, some of the roofs for the kitchen huts are thatched with banana leaves.

Figure 2.5: Some of the art and craft items made from banana leaves

Pseudo stem

In Kenya, the Pseudo stem has varied uses which include:

i) *Farm organic fertilizer*- The Pseudo stem in most cases where the farmer has no cattle is left on the farm where it becomes an organic farm fertilizer.

ii) *Animal feed* - The stem is often cut into pieces and fed to cattle in case the farmer rears them.

iii) *Ropes* - In Kenya, the leaf sheath of the pseudo stem is used for tying vegetables in bunches for sale in markets as shown in Figure 2.6, which then the consumer throws away to consume the vegetable. The leaf sheath can also be used as a rope for tying goods together for instance a bundle of firewood.

Figure 2.6: Banana pseudo stem in use for tying various vegetables into bunches

iv) *Irrigation channel* – This is common among the Taita and it's an irrigation system developed to provide water for their crops on the steep hillsides. It uses a mixture of furrows, raised furrows, banana plant leaves and hollow banana stem conduits to channel water (Finke, 2003).

v) *Head pad* - The leaf sheaths are normally used to make a head pad for the protection of the head. It protects the head from the heavy load and provides cushioning. Locally it's referred to as engata and is as shown in Figure 2.7.

Figure 2.7: Head pad on the right and head pad on use on the left.

Peduncle

The peduncle probably has minimal use in Kenya. Most of the peduncle is disposed of in urban markets together with the other refuse of the market, in the municipal dumping sites, and on the farm, it is thrown in compost pits or pit latrines and left to decompose.

Peels

There is no major use of banana peels in Kenya as they are thrown on the farms and left to compost or used as animal feed in rural areas, but in urban areas, it ends up being collected with the other municipal wastes. The peels from factories dealing with bananas are treated similarly to the rural areas where in most cases they are taken to the farm to act as organic fertilizers. The peels of ripe bananas can be seen littered in the cities and they are a nuisance to the pedestrians as they cause pedestrians to slide. It is also hard to track the peels of dessert bananas when consumed at various homesteads, but one can be able to get them from hotels and wayside fruit vendors.

Waste fruits

In Kenya, there is little of this as most of the bananas are the cooking type, such that the scratched ones can easily be consumed at home. The little percentage of waste bananas that are not fit for human consumption is fed to animals but if the farmer does not keep animals the waste bananas

are dumped into the farm, to be used to provide organic fertilizers. The bananas that get spoilt in transit to the markets or the market are mostly collected together with other market wastes.

After several material utilization (e.g. crafted items), digestion of these products for energy recovery is still possible. This should stimulate the usage of plant parts, since products may still serve a purpose even after they are thought of as unusable. So far, the only parts economically usable with one-stage digestions are spoilt or rejected banana fruits. The usage of spoilt and rejected bananas for digestion helps to reduce waste amounts and produces biogas. Since all banana residues/ wastes are organic they are capable of being anaerobically digested, they do not need to be disposed of. After the degradation, it is possible to receive fertilizer, compost, or feed with certain treatments. Therefore, no disposal is necessary in this way either.

2.3.6 Banana plant residues generation

The banana plant residues are produced at various stages of the supply chain as shown in Table 2.1.

Table 2.1 Banana plant residues Generation channels.

Place	Waste
Farm	• Pseudo stems (leaf sheaths) after banana harvest. • Spoilt bananas due to pest infestation, natural spoilage, trimming, and pre-mature harvesting. • Banana peels from the bananas consumed by the farmer and family • Banana leaves. • Peduncle if farmer consumes the bananas or sells in the retail form to neighbours
Rural assembly market	• Leaves are used to protect the banana on transportation. • Leaf-sheaths are used as ropes and head pads for banana transportation.
Urban wholesale market	• Spoilt bananas since some rot on transportation due to bruising, breakage and poor handling and infection as a result of exposure

	to dust, heat, rain, and humidity or on storage in the market due to over-ripening. • Dried banana leaves for storage of bananas. • Peduncle when bananas are sold ripe in hands.
Urban or Rural retail Market	• Spoilt bananas since some rot on storage in the market or during transportation to the market this can be attributed to loss of weight and quality due to multi-level handling. • Peduncles since most bananas are sold in hands or fingers.
Consumer premises (hotels, households, schools, hospitals, and other retail buyers)	• Banana peels (both ripe and raw). • Spoilt bananas during transportation to premises especially if bought when ripe.

From Table 2.1 it is clear that banana residues at the farm, rural assembly markets, and that in urban wholesale markets are the ones that can easily be collected and accounted for. The rest mostly are collected together with other municipal wastes and is hard to account for it. To harness biogas from the banana residues, the significant amount of residues that can be utilised are found on the farm, thus the use of the three substrates of banana plant residues (stem, leaves and peduncles) for this study.

2.4 BIOGAS

Biogas is the gas generated from organic digestion under anaerobic conditions by a mixed population of microorganisms (usually varied bacteria); it is a renewable energy source utilized both in rural and industrial areas. The composition of biogas depends on feed materials (Anunputtikul & Rodtong, 2004). The typical biogas composition is shown in Table 1. Natural anaerobic digestion is an important part of the Biogeochemical Carbon Cycle. Methane-producing bacteria also, known as Methanogens are the last group of micro-organisms in the degradation of organic matter and return the decomposed products to the environment.

The calorific value can vary from 6.0 to 10.3 kWh/m^3, increasing with a larger amount of Methane composition. The density decreases with an increasing amount of methane, so it may vary from 1.21 to 0.73 kg/m^3. The Index of Wobbe increases with increasing methane amount and lies

between 6.9 and 14.9 Kcal/mN^3. These characteristics differing from town gas may require a special application for burning and need to be controlled concerning their diversity (Naskeo Environment, 2009). In contrast to fossil fuels, when using biogas, the carbon dioxide equilibrium is preserved. Only carbon monoxide being stored in re-growing plants will be freed into the atmosphere so that it will be used by succeeding plants again. According to Kossmann et al. (2000), the calorific value of biogas of about 6 kWh/m^3 and which is equivalent to that of half a litre of diesel oil. When using biogas as a fuel, methane is a valuable component (Kossmann, et al., 2000). Table 2.2 is the typical composition of biogas produced on average from various digesters depending on the source of waste.

Table 2.2: Typical Biogas Composition (IHK, 2008), (Naskeo Environment, 2009).

Components	**Household waste**	**Wastewater treatment plants sludge**	**Agricultural wastes**	**Waste in the agri-foods industry**
Methane (% vol)	50-60	60-75	60-75	68
Carbon dioxide (% vol)	38-34	33-19	33-19	26
Nitrogen (% vol)	5-0	1-0	1-0	-
Oxygen (% vol)	1-0	< 0.5	< 0.5	-
Water (% vol)	6 (@ 40 ° C)	6 (@ 40 ° C)	6 (@ 40 ° C)	6 (@ 40 ° C)
Total Volume (% vol)	100	100	100	100
Hydrogen Sulphide (mg/m^3)	100 - 900	1000 - 4000	3000 – 10 000	400
Ammonia (mg/m^3)	-	-	50 - 100	-
Aromatic (mg/m^3)	0 - 200	-	-	-
Organochloride or organofluoride (mg/m^3)	100-800	-	-	

Well-functioning biogas systems can yield a whole range of benefits for their users, society, and the environment in general. According to Kossmann, et al., (2000), these benefits include:

i) Energy (heat, light, electricity) production.
ii) Production of high-quality fertilizer from organic wastes.
iii) Improved hygiene and sanitation, through the reduction of pathogens, worm eggs, and flies.
iv) Improved health by use of clean energy sources.

v) Workload reduction in firewood collection and cooking.
vi) Protection the environment
vii) Mitigation of climate change by reducing Green-House Gasses (GHG) Emissions.
viii) It reduces the bad odour from manure.
ix) Micro-economic benefits from sustainable energy sources, additional income sources, and increased yields from agriculture from the digestate fertilizer.
x) Macro-economic benefits through import substitution, decentralized energy generation, and carbon credits.
xi) Minimizes water pollution by use of waste that would end up in various forms of water resources, and also, reduces nitrogen eutrophication of groundwater.

Biogas production faces challenge both of economic and technical nature, which limits its use. The challenges of using biogas production include:

i) The Collection and transportation of biomass are expensive.
ii) Its heating value is low and the presence of corrosive impurities in biogas makes it unsuitable for compression and injection into pipelines.
iii) The construction of anaerobic digesters is expensive as they require to be with high precision and structural standards to minimise or avoid leaking, cracking and corrosion.
iv) The presence of other components other than methane decreases biogas efficiency and economic benefits (Sannaa, 2004).

2.5 ANAEROBIC DIGESTION

Anaerobic digestion (AD) is an established technology for waste and wastewater treatment. AD normally produces ten times less refractory biomass than aerobic treatment. Most of the chemical oxygen demand (COD) is converted to methane gas during the anaerobic digestion process. The product of anaerobic digestion is biogas and is a mixture of methane, carbon dioxide and other products (water vapour, hydrogen sulphide) that can be improved or upgraded to natural gas quality for use in heating and generation of electricity. The whole biogas-producing procedure can be divided into four distinct steps: hydrolysis, fermentation (acidogenesis), β oxidation (acetogenesis) and methanogenesis as shown in Figure 2.8.

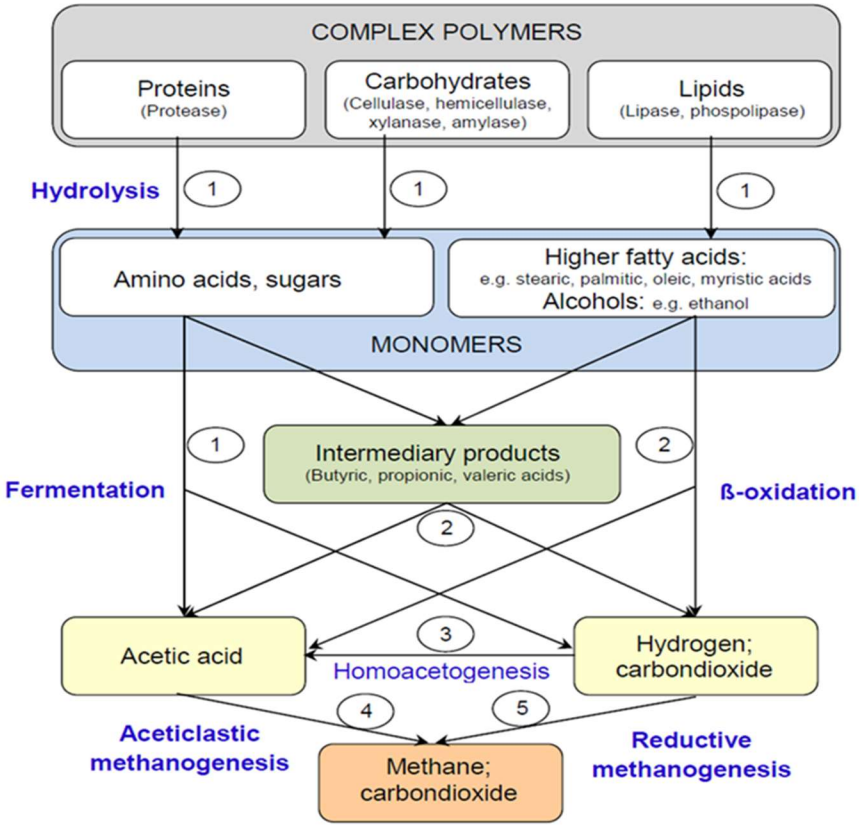

Figure 2.8: Steps of anaerobic digestion of complex polymers.

The enzymes excreted by hydrolytic bacteria are shown by the names in the brackets and the bacterial groups are shown by the numbers whereby:

1. Fermentative bacteria
2. Hydrogen-producing acetogenic bacteria
3. Hydrogen-consuming acetogenic bacteria
4. Aceticlastic methanogenic bacteria
5. Carbon dioxide-reducing methanogenic bacteria (Nayono, 2009)

2.5.1 Hydrolysis

It is the initial process; it involves the breakdown of insoluble organic polymers to a simple form that can be easily used by the anaerobic digestion microorganisms. Complex organic polymers such as polysaccharides, lipids, proteins, fat and grease are converted by extracellular enzymes to form monomers. The monomers are small-sized and easily transported across the bacteria cell membrane. Hydrolysis is the rate-limiting step energy-consuming and slow process. The general

chemical formula for an organic waste mixture is $C_6H_{10}O_4$, which is glucose. Equation 2.1 shows the hydrolysis reaction glucose is converted to simple sugar (Ostrem, 2004).

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \qquad \text{Equation 2.1}$$

2.5.2 Acidogenesis (Fermentation)

This step follows hydrolysis and is the acids forming process where acidogenic bacteria turn the hydrolysis products into simple organic compounds mostly short-chain volatile fatty acids such as acetate. The other products include the long-chain volatile fatty acids such as butyrate and propionate, ketones such as methanol and ethanol and alcohols. The acidogenesis process is very fast compared to the other steps of anaerobic digestion. The regeneration time for fermentation bacteria is approximately 36 hours. The type of bacteria culture and the digester conditions determines the specific concentrations of products produced. Typical reactions for acidogenesis are shown in Equation 2.2, glucose is converted to ethanol, and in Equation 2.3, glucose is converted to propionate (Ostrem, 2004).

$$C_6H_{12}O_6 \leftrightarrow 2\ CH_3CH_2OH + 2CO_2 \qquad \text{Equation 2.2}$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2\ H_2O \qquad \text{Equation 2.3}$$

Acetate is an important organic acid as it can be used directly as a substrate by methanogenic bacteria. (Nayono, 2009)

2.5.3 Acetogenesis

Acetate is produced in both acidogenesis and acetogenesis whereby the acetogenic bacteria convert long-chain volatile fatty acids into carbon dioxide, hydrogen and acetate as shown in Equation 2.4, propionate is converted to acetate (Nayono, 2009).

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad \text{Equation 2.4}$$

Acetogenesis is therefore a process whereby long-chain Volatile Fatty Acids, Ketones, and alcohols are converted into acetate and hydrogen. The acetogenesis stage involves the conversion of glucose (Equation 2.5), bicarbonate (Equation 2.6) and ethanol (Equation 2.7) to acetate.

$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2\ CO_2 + 4H_2$ Equation 2.5

$2HCO_3^- + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O$ Equation 2.6

$CH_3CH_2OH + 2H_2O \leftrightarrow\ \ CH_3COO^- + 2H_2 + H^+$ Equation 2.7

The acidogenic and acetogenic bacteria work well in acidic conditions of pH between 4.5-5.5 (Ostrem, 2004).

2.5.4 Methanogenesis

This is the final step for anaerobic digestion where methane is produced. The Methanogenic anaerobic bacteria (methanogens) are involved, they are fastidious bacteria are found in the rumen of herbivores in deep sediments. The Methanogens convert acetate to methane (Equation 2.8 followed by 2.9) or conversion of alcohol, such as methyl alcohol to methane (equation 2.10). There is also carbon dioxide reduction by hydrogen in the Methanogenesis stage (equation 2.11).

$2\ CH_3CH_3OH + CO_2 \leftrightarrow 2\ CH_3\ COOH + CH_4$ Equation 2.8

$CH_3COOH \leftrightarrow CH_4 + CO_2$ Equation 2.9

$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O$ Equation 2.10

$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$ Equation 2.11

Methanogens work well in a neutral to the slightly alkaline environment and are very sensitive to change such that if pH falls below 6, they cannot survive, like in Equations 2.12 and 2.13. Methanogens have a very slow regeneration rate compared to acetogens of about five to sixteen days and thus, methanogenesis is the rate-controlling step and describes the kinetics of the whole digestion process.

$CH_3COO^- + SO_4^{2-} + H^+ \rightarrow 2HCO_3 + H_2S$ Equation 2.13

$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3^- + NH_4^+$ Equation 2.14

Anaerobic digestion takes place in four steps and all these steps take place concurrently and synergistically (Ostrem, 2004).

2.6 PARAMETERS AND METHANE PRODUCTION OPTIMIZATION

The efficiency of a biogas plant depends on various operating parameters/ conditions which include pH, loading rate, and temperature that can be varied to obtain favourable conditions for an optimal yield of biogas (Yadvika et al., 2004). These operating conditions/ parameters are as follows.

2.6.1 Temperature

There are three temperature ranges of anaerobic degradation under which the anaerobic bacteria consortia function and they include, degradation at ambient temperature psychrophilic range that is less than 30°C, mesophilic degradation that ranges between 33°C to 40 °C and thermophilic degradation that ranges between 50°C to 60°C. At higher temperatures decomposition takes place at a faster rate. Technically only the mesophilic and thermophilic ranges are considered since at psychrophilic temperature ranges the anaerobic degradation is very slow. Thermophilic anaerobic degradation is faster and more efficient than mesophilic degradation but it is rarely used due to the high energy required to maintain the high temperatures. Thermophilic digestion is more intense, has high efficiency of removal of Volatile Suspended Solids, and yields more biogas (Vindis P., 2009). The length of the fermentation period depends on the temperature (Muvhiiwa, R. F et al.,2016).

2.6.2 pH

The most suitable pH levels for methane-producing bacteria are neutral or slightly alkaline rates. pH is an important parameter to consider as it affects the growth of microorganisms during anaerobic digestion. The desired operating pH of the digester is 6.8–7.2 and should be maintained by feeding it at an optimum loading rate. At pH above 5.0, the efficiency of methane production is more than 75%. The pH of the digester is affected by the quantity of carbon dioxide and volatile fatty acids produced during the degradation process. Yadvika et al. (2004) stated that the concentration of volatile fatty acids in particular acetic acid should be below 2000mg/l for anaerobic digestion to take place at normal operating Ph ranges.

2.6.3 Pre-treatment

Feedstock sometimes requires pre-treatment to alter its structure and make it easily degradable to increase the methane gas yield. Pre-treatment converts complex organic compounds to simpler

molecules which, are easily utilized by the anaerobic microorganisms (Yadvika et al., 2004). Pre-treatment can be done to improve the hydrolysis yield and total methane yield (Hendriks & Zeeman, 2008).. Pre-treatment releases the lignin from the cell structure and increases access to the available nutrients. Different pre-treatment methods that are physical, chemical and biological have been assessed for the breakdown of lignin-cellulosic complexes. The various pre-treatment methods include thermal process, use of gases, use of chemicals (acids, solvents, bases and Oxidants) and bio delignification (Bauer et al., 2009).

2.6.5 Particle size

Particle size has some influence on gas production. The size of the feedstock should not be too large to avoid clogging the digester and also large particles are difficult to be digested by the anaerobic microorganisms (Kossmann, et al., 2000). Smaller particles provide a large surface area for utilizing the substrate by the microorganisms and this leads to increased microbial activity and gas production (Yadvika et al., 2004). For large particle size, the material is solubilized for a long time and also less surface area is available for bacterial degradation thus, less gas production (Sharma et al., 1988).

2.6.6 Carbon/Nitrogen ratio

Carbon (C) and Nitrogen (N), are the most important nutrients for the anaerobic bacteria and different substrates have different amounts of these two elements. Fermentative bacteria require thirty times more carbon than nitrogen. According to (Tanzania Traditional Energy Development Organisation, 2006) 30/1 is the optimal carbon-nitrogen ratio (C/N) ratio for the digester input. According to Ostrem (2004) low C/N ratio, leads to pH above 8.5, due to high ammonia production and the excess ammonia reduces the quality of digestate. A high C/N ratio will cause fast absorption of nitrogen by the methanogens and reduce the methane production rate.

2.6.7 Mixing (Agitation)

Constant mixing of digester contents ensures a uniform mix of substrates and micro-organisms, which improves the digestion rate and efficiency and maintains process stability. According to Kossmann et al. (2000), mixing is important because :

i) Takes out the metabolites from methanogenesis (gas)
ii) Hinders sedimentation and scum formation.

iii) Blends the fresh substrates with the inoculum (inoculation)
iv) Avoids the formation of voids that reduces the effective digester volume.
v) Uniform distribution of bacterial density.
vi) Prevents conspicuous temperature differences in the digester.

Mixing and stirring the digester to ensure optimum contact between microorganisms and substrate which improves the yield of the anaerobic process. Mixing, stirring and agitation can be achieved in various ways, by use of devices such as impellers, gas sparging and recirculation of slurry (Yadvika et al., 2004).

2.6.8 Inoculum (Seeding sludge)

Seeding sludge has a population of microorganisms for the digestion process, it is used for starting up the anaerobic digestion process or during digestion to accelerate the process. Commonly used inoculum includes digested sludge from an operating biogas plant, Wastewater treatment plant, or cow dung slurry. The addition of seeding sludge increases the gas yield, reduces the retention period, and also produces good quality biogas with high methane by the addition of inoculum (Yadvika et al., 2004). During digestion, if there are excess volatile fatty acids from overloading, it can be rectified by reseeding.

2.6.9 Organic loading rate

The organic loading rate (OLR), is an important parameter as biogas production depends on the loading rate and it determines the input of volatile fatty acids. Increasing the OLR will cause an increase in acidogenic bacteria since they reproduce very fast given enough substrate and this will produce acids that the methanogens that reproduce slowly cannot consume the acids at similar rates. The pH in the digester will then decrease, killing more of the methanogens and finally stopping the digestion process. To detect this, there will be low biogas production and low pH (Ostrem, 2004).

2.6.10 Hydraulic Retention Time (HRT)

Retention time or residence time is the degradation time of the organic matter or the average time which the substrate is in the digester. It can also be measured by the COD or BOD of effluent. The longer the retention time of substrates under conducive operating conditions, the higher the

degradation. There is the optimal time in which benefits of anaerobic digestion are achieved efficiently and effectively and thus, the reaction rate will decrease with increased residence time beyond optimal time (Ostrem, 2004).

The longer the materials stay in the digester the higher the retention time and the higher the yield of biogas. Approximately 50 days is enough to complete degradation and gas extraction. Digester volumes are reduced and thus reduction of retention time for cost-benefit ratio purposes.
Reduced retention time reduces the digester size thus saving on the capital cost. Low retention times often cause the washout of active bacteria while high retention time leads to larger volumes of the digester, thus need to reduce the retention time of biogas plants based on the substrates (Yadvika et al., 2004).

2.6.11 Total Solids Concentration

Total solids concentration is the amount of degradable material in a unit volume of slurry. The lower the concentration of the total solids, the less the amount of degradable material and thus, the lower the yield of biogas. When the total solid concentration is high the mixture becomes too dense to efficiently move around the digester, this impairs the movement of methanogens within the substrate, lowering biogas yield. There are no guidelines for specific biogas production at any specific total solids concentration (Kossmann, et al., 2000).

2.6.12 Moisture content

Moisture content is a useful parameter in anaerobic digestion, as it helps in the transportation of nutrients, enzymes, microorganisms, and products. It also aids in the hydrolysis of complex organic polymers. High moisture contents ease the digestion process by dissolving readily degradable organic matter.

2.6.13 Nutrients

The microorganisms (bacteria) require mineral nutrients in addition to the supply of organic matter as a source of carbon and energy. These mineral nutrients are calcium, nitrogen, magnesium, sulphur, potassium, phosphorous and trace elements such as zinc, iron, manganese and selenium. The concentration of these minerals should be enough, not too high in concentration to cause an inhibitory effect. From the study, Kossmann et al. (2000) recommend analysis to determine which

amount of which nutrients are required for optimal performance of the digester. Agricultural residues or sewage contain sufficient amounts of these mineral nutrients.

2.6.14 Inhibitory Factors.

This is the hindrance of the anaerobic digestion process by toxic substances in the mix resulting in the altering of biogas production and organic removal and failure of the digester. The toxic substances are either substrates components or digestion process products. The inhibitory or toxic substances for the anaerobic digestion process are;

i) Hydrogen sulphides cause low methane yields due to competition for organic and inorganic substrates between methanogens and sulphate reducing. The sulphides also cause toxicity to various anaerobic digestion bacteria.
ii) Excess nitrogen leads to the formation of Ammonia which increases the pH and thus inhibition of certain enzymatic reactions and also, increases energy requirements to overcome the toxic conditions.
iii) Metal ions such as potassium, sodium, magnesium and calcium are found in the digestate. These nutrients are required in moderate amounts to start up microbial growth. A higher concentration of the metal ions will lead to slow growth, and inhibition or toxicity. Salt toxicity leads to bacterial cells' dehydration from osmotic pressure.
iv) Heavy metals accumulate to toxic levels since they are not biodegradable, and they are required in anaerobic digestion in very small concentrations to stimulate microbial growth in the reactor.
v) Organic compounds such as long-chain fatty acids, chlorophenols, halogenated aliphatic and lignin/lignin-related compounds have an inhibitive potential to the anaerobic digestion process. According to Nayono (2009) increase in hydrophobic organic pollutants in bacteria, membranes causes them to swell, change the ions gradient and ultimately break the cell membranes.

2.7 ANAEROBIC DIGESTERS CONFIGURATION.

Anaerobic digesters can be engineered, configured and designed to operate using several different process setups. There are two basic configurations according to the feeding method of the substrate; which are the batch digesters and the continuous digesters (single-stage or two or multi-stage). Another way of classifying digesters is based on the moisture content of the substrate that

is wet or dry digestion. Digesters can also, be classified based on operating temperatures the thermophilic or mesophilic digesters and the design of the reactors that are horizontal or vertical digesters (Nayono, 2009).

2.7.1 Batch versus Continuous

For batch digesters, the reactor vessel is loaded once with raw feedstock for a certain period and can be inoculated (inoculum added). It is then sealed and left until complete degradation has occurred. With continuous digesters, the substrate is regularly and continuously fed into the digester. In continuous digesters, plug flow, Continuously Stirred Tank Reactor, and Upflow Anaerobic Sludge Blanket (UASB) systems. Hybrid batch digesters and one-stage sequential batch are the batch digesters examples. (Nizami & Jerry, 2010).

Batch digesters are easy to build, once the feedstock is loaded, the retention time depends on various factors such as the microbial bacteria if any, the substrate, the temperature and other factors. After digestion, the digestate is removed since it is a one-time process that is favourable for feeds with high solid contents and seasonally produced biomass feeds. The digestate from a batch digester can be used as an inoculum. The main advantage of batch reactors is one can access the degradability of the substrate (Jigar, 2010). Batch processes are often preferred in developing countries because of the low investment costs as they do not require sophisticated mixing or agitation equipment, or expensive high-pressure vessels (Nayono, 2009).

According to Jigar (2010), the feedstock is fed regularly in a continuous reactor, the biogas production is continuous and there are no interferences between feeding the feedstocks and digestate removal. Continuous digesters are used for large-scale operations.

2.7.2 Single versus Two / Multistage

Anaerobic digestion takes place in four steps which can be divided into two main stages;

i. The first step involves hydrolysis, acidification and liquefaction
ii. The second step involves the conversion of carbon dioxide, hydrogen and acetate to methane.

These steps can be further classified into a single stage or two / multistage systems. The single-stage is where all the processes take place concurrently under the same operating conditions in a single reactor. These operating conditions are the same for all steps despite different optimal pH and growth rates for the various microbial groups for the different steps.

The two / multistage systems have separate digesters for each step, thus optimizing the digestion process. The first digester conditions are adopted for hydrolysis and acidification, and the product of the first digester is moved to the next digester for methanogenesis (Nayono, 2009).

2.7.3 Thermophilic versus Mesophilic

Mesophilic degradation takes place at 33-40°C and thermophilic degradation at 50-60°C**.** The energy requirements for thermophilic conditions are high but these conditions offer a high hydrolysis rate of cellulose compared to the mesophilic conditions. Thermophilic digestion offers advantages of high metabolic rates and high destruction of pathogens, though, the process is less stable as compared to mesophilic conditions. Table 2.3 highlights the advantages and disadvantages of conducting digestion in thermophilic and mesophilic temperatures.

Table 2.3: Advantages and Disadvantages of Mesophilic and Thermophilic Anaerobic Digestion conditions (Chaudhary 2008)

Parameter	Mesophilic	Thermophilic
Temperature	30-40 ˚ C	50-60 ˚ C
Residence time	15-30 days	10-20 days
Total solids (Wet) (Dry)	 10-15% 20-40%	 10-15% 20-40%
Advantages	• Tolerant and Robust process	• High gas production • Sensitive to environmental variables • Faster throughout
Disadvantages	• Low gas production • Large digestion tanks	• Needs effective control

2.7.4 Wet versus Dry

The anaerobic degradation process can be either wet or dry depending on the total solid concentration of the feedstock. In a wet process, the total solids concentration of the feedstock is

less than 15% and in a dry process, the total solids concentration of the feedstock is between 20% to 40%. In wet digestion processes, the solid waste has to be prepared to the correct solids concentration by adding water. Continuously stirred tank reactors (CSTR) use the wet process. The advantages of the wet digestion process include dilution of inhibitory substances by process water and the disadvantages are the use of large quantities of water and energy for heating, complex pre-treatment methods and reduced operation volumes due to sedimentation of inert substances.

The main limitation for dry anaerobic digestion reactors is the heterogeneous distribution of substrate and microorganisms as well as low mass transfer under high solid content. Biogas injection is used for mixing the digester content, though, this does not result in complete mixing of the digestate. This results in various reactions taking place in different sections of the digester thus hindering achieving optimal action of various microbial groups. Plug flow reactors are preferred for the dry anaerobic digestion process. Dry anaerobic digestion requires little pre-treatment and has a high loading rate (10 kg oDM / m^3 per day or more).

2.8 INFORMATION PROVIDED BY FERMENTATION TESTS CARRIED OUT AS PER VDI-4630

Fermentation tests were carried out following VDI-4630 information regarding:

i) Fundamental evaluation of biogas yields and the anaerobic degradability of a material or mixture of materials.
ii) Qualitative appraisal of the speed of degradation of a material under investigation.
iii) Qualitative evaluation of the inhibitory effect of the material under investigation in the range of concentrations in the test.

The fermentation batch test does not provide information with regards to: -

i) Process stability in reactors that are continuously fed with the material or mixture of materials under investigation.
ii) Biogas production under practical conditions due to possible negative and possible synergistic effects.
iii) Mono-fermentability of the substrate under process conditions.
iv) The limits of organic loading rate per unit volume.

2.9 ANAEROBIC DIGESTION OF LIGNOCELLULOSIC MATERIALS

Lignocellulosic biomass is mainly composed of lignin, cellulose and hemicellulose and varies depending on plant type, growth conditions, and maturation both in quantity and quality. Lignocellulosic biomass is a good feedstock for biogas production since it does not compete with food production and is readily available; however, its complex and rigid structure hinders its complete use as a source of energy (Behnam et al., 2020).

The fundamental shape of cellulose is created from the hydrogen bonding of glucose polymers, which results in stiff rod crystalline structures (fibrils). The Cellulose fibrils are enclosed closely in a lignocellulosic matrix making them resistant to enzymatic hydrolysis. Cellulose is insoluble in water and has high tensile strength due to its strong crystalline structure and it is hard to degrade biologically (Aya & Gabriel, 2019).

Hemicellulose is a heteropolymer of different polysaccharides which are glucose, xylose, mannose arabinose, sugar acids and galactose. Hemicellulose contains a short chain of sugar and is present in the cell walls of most plants. Hemicellulose is degraded biologically by hydrolytic and hemicellulase enzymes (Behnam et al., 2020).

Lignin is an amorphous heteropolymer consisting of three-dimensional phenyl propane units that make it complex in nature and insoluble. It is rigid and also limits the degradation process. The presence of lignin reduces the methane yield. Lignin forms the layer that protects the cellulose and hemicellulose in the cell wall, it thus acts as a barrier for any enzymatic hydrolysis of the hemicellulose and cellulose (Aya & Gabriel, 2019). Its covalent bonds and also phenyl constituents make it hard for any enzyme degradation.

The amount of biogas available from lignocellulosic materials can be very low and mostly dependent on the accessible surface area, cellulose polymerization and crystallinity, protection of lignin, cross-linkages of hemicellulose and other process-induced factors. To obtain optimal biogas from lignocellulosic biomass, they need to be pre-treated before digestion.

According to Behnam et al., (2020), effective pre-treatment methods are those that meet the following requirements: -

i) Produces low crystallinity of cellulose.

ii) Results in increased surface area for the enzymatic reaction.

iii) Produces a water-soluble substrate for digestion.

iv) Breaks the hydrogen bonds between cellulose and hemicellulose.

v) Results in none or low concentration of Inhibitors in the feedstock.

vi) Has minimal utilization of chemicals and energy.

2.10 BIOGAS UTILIZATION

The various ways of biogas utilization include the production of electricity, steam, heat and chemicals and can also be used as a biofuel. Biogas uses are achievable since they can be used in situ, can be transported and also can be stored with ease. The various utilization pathways are illustrated in Figure 2.9.

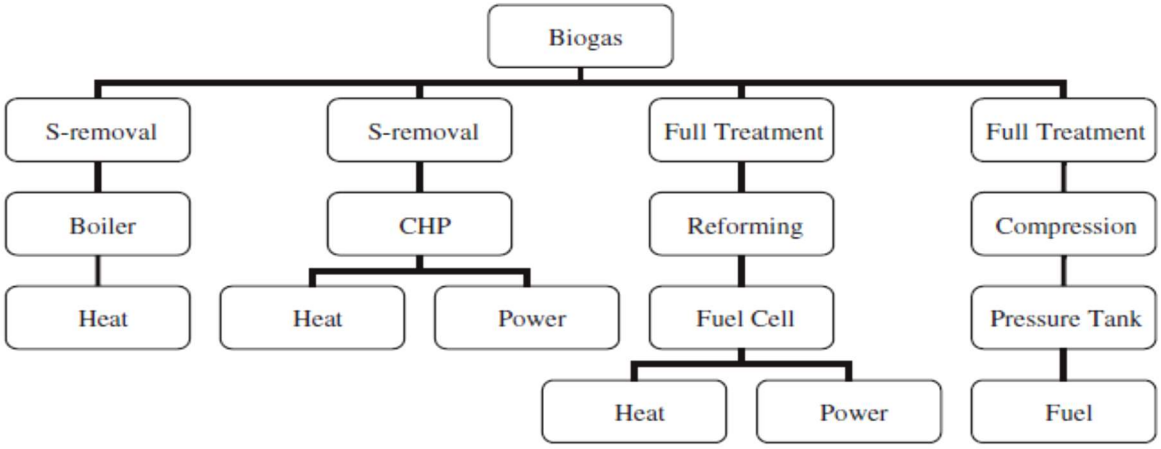

Figure 2.9: Biogas utilization and required upgrading (Appels et al.,2008).

After condensate and particulate removal from the biogas, it is compressed, cooled, dehydrated and transported by pipeline for use as fuel for boiler or burner. Owing to the low heating value for biogas minor modifications are required (Moser, 1997). Generation of Electric Power using gas turbines, steam turbines, fuel cells and reciprocating engines is another use of biogas.

Biogas can be treated to remove the carbon dioxide and other impurities to form a high-energy gas, it can also be treated to natural gas quality for use as vehicle fuel (Appels et al., 2008). Biogas can be converted to other forms such as methanol, ammonia, or urea, conversion to methanol is more feasible. To convert methane to methanol, water vapour and carbon dioxide are removed (Moser, 1997).

2.11 BIOGAS FROM BANANA WASTE

The potential for methane production depends on the status, type and constituents of the organic materials undergoing fermentation and these affect the quality of biogas (Deivanai & Bai, 1995). Banana plant residues consist of waste or rejected bananas, Pseudo stem, peels, leaves and peduncle: each part has its biogas production potential and quality. There have been researches that were conducted to establish the bio-methanation potential of the various banana plant residues as shown in Table 2.4.

Clarke et al. (2008) conducted laboratory experiments to see if there is a potential of getting sufficient methane from rejected bananas and peduncles. The batch-fed digestion for reject bananas was conducted in a 200L reactor and no inoculum was used. A highly buffered 200L batch digester was used at first to establish the microbial culture. The reactor for the reject bananas was started by the digestate of the mature batch reactor, for 70 days, average working volume of 160L, loading conditions of 0.6 kg VS $m^{-3}d^{-1}$, and the yield was 398 ± 20 L CH_4/kg oDM.

Bardiya et al. (1996) used a 2L digester using cow dung as the inoculum for 40 days, the yield was 190L CH_4 / kg TS, when the banana peel was dried and converted to powder form the yield increased to 201L CH_4 /kg TS. Gunaseelan (2004) studied the anaerobic digestion of banana peels of 8 different cultivars in powder form, 135ml bottles were used with 0.5g of the substrate with lab scale digester sludge used as inoculum. The yield was between 0.243-0.322 m^3CH_4/kg oDM. Bardiya et al. (1996), then concluded that bio-methanation of banana peel wastes suggests its economically viable. The energy generated in the form of methane when utilized efficiently not only improves the overall economy but also provides on-site solutions to waste management problems. Mandal & Mandal (1997), conducted studies on banana leaves and found that they could produce at least 0.0018m^3 of biogas but Reddy et al. (2010), confirmed that banana leaves have a high concentration of hemicelluloses and lignin which inhibits the availability of cellulose for fermentation by the isolates. Hemicellulose and lignin are complex polymers and are not easily degraded by bacteria.

Kalia et al. (2000), conducted experiments using banana stems under thermophilic and mesophilic conditions, the biogas yield was found to be 267 ± 271 L/kg TS, under mesophilic conditions and, 212 ± 229 L/kg TS, in the thermophilic range. In the digestion of banana stems, it was found that

the high fibre content in the stems inhibited the methanogenesis process, and due to this factor, a two-stage digester was used for the experimental setup. Mohammad, et al. (2016) conducted the Biochemical Methane Potential experiments for different fractions of the banana stalk, peel, flesh and the whole unpeeled for 35-days at 37°C using a 2L digester. The methane yields were 0.26, 0.37, 0.35, and 0.32 m^3/kg VS (Volatile Solids) for stalk, flesh, unpeeled banana and peel respectively.

Spyridon et al. (2019) looked at the effect of anaerobic digestor performance due to organic loading (OL) and the addition of cow manure (CM) with the banana peel as substrate. The study concluded that the biogas yielded per day had no interdependence with the organic loading rate and the cow manure content. (Clarke et al. (2008), experimented using both reject bananas and peduncles, thus it was not clear what fraction of the gas was for peduncle and what fraction of the gas was for reject bananas.

From the literature, as outlined in this study banana plant residues can be better managed by turning them into biomass feedstock. The results from the studies in Table 2.4 shows the potential of the banana plant residues and their suitability to be used as a feed stock for biogas generation, but, the major drawback is that the feedstock is not fully degraded (Tock et al., 2010).

To be able to further analyse the economic viability of using banana plant residues as biomass feedstock there is a need to evaluate the composition of various banana constituents as shown in Tables 2.5 and 2.6. The values are according to a study conducted by Oliveira et al. (2007) the banana plant was divided into three different morphological parts rachis, pseudo-stems and foliage. The Pseudo stem was further divided into floral stalks and leaf sheaths. The foliage was divided into midrib, petioles and leaf blades as shown in Figure 2.10. Mohapatra et al. (2010) studied the banana plant's chemical composition and the results are in Table 2.6.

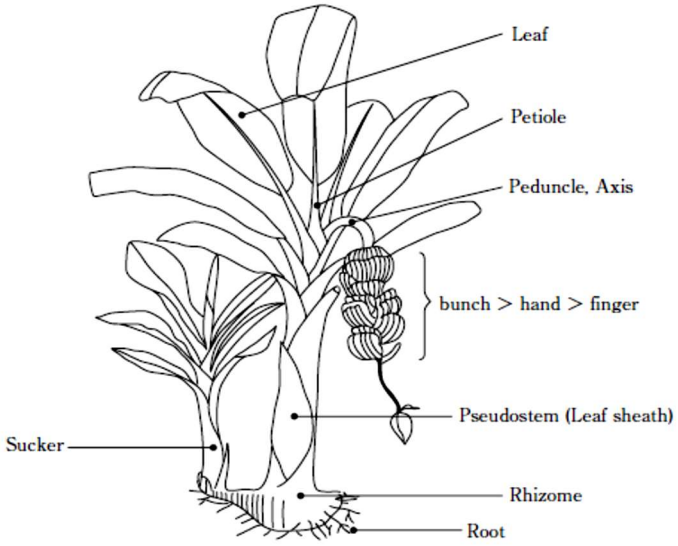

Figure 2.10: Diagram showing the plant parts (JAICAF, 2010)

Table 2.4: Methane yield as shown by various studies

Study	Banana part	Total Solids reduction (%)	Organic Solids reduction (%)	Retention days	Methane yield (m^3CH4/kg TS)
Sharma et al. (1988)	Cut, ground banana peels	34.4-42.9	31.7-37.3	56	0.221-0.338
Kalia et al. (2000)	Sundried banana stems (mesophilic)	35-45	47-55	57	0.081-0.196
Kalia et al. (2000)	Sundried banana stems (Thermophilic)	23-36	28-47	24	0.084-0.171
Deivanai & Bai (1995)	Banana trash	25.3	39.6	30	0.0066
Ilori et al. (2007)	Banana peels		35		0.0088
Ilori et al. (2007)	Plantain Peels		35		0.002409
Bardiya et al. (1996)	Powdered banana peel	35	40	25	0.096
Bardiya et al. (1996)	Chopped banana peel	36	41	25	0.103
Bardiya et al. (1996)	Powdered banana peel	30	34	40	0.127
Bardiya et al. (1996)	Chopped banana peel	28	31	40	0.125
Clarke et al. (2008)	Mechanically cut green banana fruit and banana peduncle			70	0.398 m^3CH4/kg oDM
Gunaseelan (2004)	Powdered banana peels			100	0.243-0.322m^3CH4/kg oDM
Mandal & Mandal (1997)	Banana leaves			90	0.0018m^3 biogas
Khan et al. (2009)	Banana stem			35	0.256m^3CH4/kg oDM
Khan et al. (2009)	Banana peels			35	0.322 m^3CH4/kg oDM
Khan et al. (2009)	Banana plant residues fruits.			35	0.367 m^3CH4/kg oDM

Chengming Zhang (2013)	Banana stem co-digested with swine manure	48.5	70.4		0.232 m^3CH4/kg VS
Mohammad, et al. (2016)	Banana stalk			35	0.256 m^3CH4/kg VS
Mohammad, et al. (2016)	Banana peel			35	0.322 m^3CH4/kg VS
Mohammad, et al. (2016)	Banana flesh			35	0.367m^3CH4/kg VS
Mohammad et al. (2016)	Whole unpeeled banana			35	0.349 m^3CH4/kg VS
Divyabharathi et al. (2017)	Combined banana plant residues				0.35 l/kg/day
Divyabharathi et al. (2017)	75% mashed banana peel with 25% cow dung				3.85 l/kg/day
Spyridon et al. (2019)	Banana peel with 10% cow manure				50.2mL/g VS/ day
Spyridon et al. (2019)	Banana peel with 20% cow manure				48.66mL/g VS/ day
Spyridon et al. (2019)	Banana peel with 30% cow manure				62.78mL/g VS/ day

Table 2.5: Chemical composition of different parts of 'dwarf cavendish banana plant (% of organic dry matter weight) (Oliveira et al., 2007)

Components	Petioles/midrib	Leaf-blades	Floral stalk	Leaf-sheaths	Rachis
Ash	11.6	19.4	26.1	19.0	26.8
Extractives[a]	5.9	16.1	17.6	12.6	17.6
Dichloromethane	1.2	5.8	1.4	1.4	1.5
Ethanol/toluene	0.9	2.6	1.1	2.1	1.4
Water[b]	3.8	7.7	15.1	9.1	14.7
Lignin	18.0	24.3	10.7	13.3	10.5
Insoluble[a]	16.8	22.0	9.8	12.6	9.6
Soluble	1.2	2.3	0.9	0.7	0.9
Holocellulose[a]	62.7	32.1	20.3	49.7	37.9
Hemicellulose A[a]	14.8	6.7	2.8	7.2	3.9
Hemicellulose B[a]	6.7	1.9	2.7	4.2	3.6
α-Cellulose[a]	39.5	20.7	14.4	37.1	28.4
Cellulose[a]	31.0	20.4	15.7	37.3	31.0
Pentosanes[a]	16.2	12.1	8.0	12.4	8.3
Starch	0.4	1.1	26.3	8.4	1.4
Proteins	1.6	8.3	3.2	1.9	2.0

[a] Corrected for ashes content

[b] Corrected for starch content

To calculate the biogas potential for solid substrates the following information is required:

- Amount of the solid substrate in tons per year.
- Availability of the substrate since it should be available throughout the year or easily stored for use when required.
- Total solids (TS) content of the substrate (% of the fresh matter, FM)
- Organic dry matter (oDM) content (% TS)
- Biogas potential for the substrate (m^3/ kg oDM)
- Methane content in the biogas (%) (Fischer, et al., 2010)

Table 2.6: Chemical composition of different parts of banana plant (Mohapatra et al., 2010)

	Pseudo stem	Petioles/midrib	Leaf-blades	Floral stalk	Leaf-sheaths	Rachis
Glucose	74.0†	68.1†	60.0†	79.8†	74.2†	31.8†
Xylose	13.1†	23.6†	17.5†	9.3†	13.8†	14.0†
Galactose	2.5†	1.1†	3.8†	2.9†	2.2†	1.7†
Arabinose	9.1†	4.9†	15.5†	5.1†	7.5†	4.1†
Mannose	1.3 †	1.5†	2.3†	2.2†	1.5†	2.9†
Rhamnose	-	0.8†	0.9†	0.7†	0.8†	0.7†
Lignin	12.0†	18.0†	24.3†	10.7†	13.3†	10.5†
Cellulose	34.0-40.0†	31.0†	20.4†	15.7†	37.3†	31.0†
Holocellulose	60-65†	62.7†	32.1†	20.3†	49.7†	37.9†
Ash	14.0†	11.6†	19.4†	26.1†	19.0†	26.8†
Potassium	33.4*	9.4*	11.6*	23.1*	21.4*	28.0*
Calcium	7.5*	32.3*	8.0*	0.6*	5.5*	0.6*
Magnesium	4.3*	2.9*	1.1*	0.5*	1.9*	0.3*
Silicon	2.7*	7.0*	24.9*	7.8*	2.7*	1.2*
Phosphorus	2.2*	0.7*	0.7*	0.7*	0.9*	1.7*
Pentosans	-	12.1†	12.1†	8.0†	12.4†	8.3†
Starch	-	1.1†	1.1†	26.3†	8.4†	1.4†
Proteins	-	8.3†	8.3†	3.2†	1.9†	2.0†

† Expressed in terms of % molar proportion

* Expressed in % ash basis

2.12 DIGESTATE

Digestate is the remaining solid in the digesters after anaerobic digestion. The digestate is in fibrous and liquor form combined. The quality of the digestate depends on the type of feedstock and most digestate has nutrients including carbon in a stabilized form. The digestate produced from anaerobic digestion is considered a superior fertilizer compared to the undigested material. This is because the anaerobic digestion process increases the nitrogen availability of the material. Frequently anaerobic digestate is separated into its liquid and solids parts. The solid part is used as a soil amendment, while the liquid fraction is used as a liquid fertilizer. The concentration of nutrients in liquid digestate is relatively low due to the presence of large volumes of water. This increases the operational cost associated with the transport and application of the material to land.

To overcome these problems liquid digestate can be dewatered through the use of ultra-filtration and reverse osmosis to produce a more concentrated liquid fertilizer (Humphries, 2011).

Excess heat from the power plant can be used to dry the digestate to a dry matter content of 80% to 90%, using the dried digestate as solid fuel is an alternative and this reduces costs for storage and transport, as the digestate is dried near the biogas plant. The bulky material can be pelletized, to produce a storable and transportable product with nearly consistent properties (Kratzeisen et al., 2010). The remaining ash after burning the pellets has nutrients such as potassium, phosphorus and calcium with defined composition and high concentration and thus a valuable fertilizer. After burning, the heavy metals such as lead, zinc and cadmium found in the digestate feedstock are also present in the ash, especially the highly volatile heavy metals. The pellet's properties will determine the combustion behaviour, thus to guarantee a uniform and consistent fuel quality the feedstocks should have the same properties consistently. The digestate should be pelletized without any additives and the mechanical durability should be per standards for pellets. From studies by Kratzeisein et al. (2010) the fuel has a characteristic odour and a high ash content of 15–20%, thus this fuel should be used close to the point of manufacture.

The energy content of solid digestate is in the region of 14 MJ/kg, which is slightly lower than the energy content of raw biomass (e.g. miscanthus or wood chip). However, the use of solid digestate as fuel is advantageous because the amount of energy extracted per ton of anaerobic digestion feedstock is increased as energy is harnessed through anaerobic digestion and combustion. Reliance on energy crops is reduced, easing pressure on land for food and fuel production (Humphries, 2011)

Alternatively, pelletized digestate can be used as a solid fertilizer. The advantage of pelletizing the digestate is that it produces a more stable product that can be stored for longer periods without degradation. There are several additional advantages to producing solid digestate fuel pellets, including increasing the density of the digestate; this reduces transportation costs as more material can be transported per vehicle movement; reduced moisture content as moisture is evaporated during the pellets-making process. Typically, the moisture content of the pellet is less than 15 %, making the digestate a more stable product. Improved fuel combustion handling properties that mean fuel handling will be easier as fuel blockages are less likely to occur (Humphries, 2011).

Solids Digestate when dried can be used as a bedding for livestock saving on costs for bedding, especially for dairy and livestock farms. The excess solid digestate may be an income source and a way of nutrient transfer if sold to other farmers for use as a soil amendment or bedding. Solid digestate used for bedding requires careful handling to ensure there is low or no pathogen in it, and to maintain a healthy environment for the livestock.

Solid digestate can be used as compost manure on farms, providing sources of stabilized carbon and other nutrients. Construction materials such as medium-density fibre board and wood/plastic composite material have been developed using solid digestate. These construction materials are both mechanically stable and also good aesthetically (Animal Manure Management Community, 2010).

2.12.1 Digestate from banana plant residues

The banana plant residues do not contain human pathogens and they are free of heavy metal, glass and plastic making them have desirable qualities for compost. The pH of compost is usually around 5 to 7.5 and with controlled buffer addition, this can be achieved. The particle size of the compost can be coarsely shredded and used as mulch or reduced and used as a soil conditioner. If the compost is to be of nutritional value to the soil, then, the Total Nitrogen in the dry solid and liquid extract should be more than 0.6% (w/w) and 200mg/L respectively. The banana plant residues meet these criteria and also additionally it has other nutrients which are Sodium, Magnesium, Calcium, Potassium and Phosphorus.

The banana plant residues digester produces high amounts of wastewater. According to Clarke et al, (2008), the main components of the wastewater from the banana digester are COD, which was over 6000 mg/l, and potassium at 4200 mg/l, these levels of Potassium are high and are not acceptable for most crops and livestock

2.13 MODELLING THE ANAEROBIC DIGESTION PROCESS

Anaerobic digestion is a complex process involving various bacterial populations and substrates. Usually, such processes contain a particular step, the so-called rate-limiting or rate-determining step, which, being the slowest, limits the rate of the overall process. A limiting step is "that step

which will cause process failure to occur under imposed conditions of kinetic stress" (Lyberatos & Skiadas, 1999). Though the anaerobic process is a natural process that has been existing for many years, there is a demand to comprehend and improve the process.

Mathematical modelling comes in as a tool to aid in understanding the complex process of conversion of organic substances to biogas and other gases through various bacteria groups. With the current trends in advanced computer applications modelling comes in as an easy tool to demonstrate various complex processes. The whole modelling process (selecting a model structure, identifying the parameter values, and planning the experimental measurements) should be coherent with the objective pursued. In general, the three most common objectives of using a model are: understanding the system's behaviour and interaction of components; quantitatively expressing or verifying a hypothesis and predicting the behaviour of the system in the future or under other similar circumstances (Andres, et al., 2011).

Various models are designed to meet specific objectives; they can be designed depending on the process understanding, dynamics of simulation, optimization and controls. Models have unknown parameters for example Kinetic parameters, stoichiometry and initial conditions which are approximated from experimental data. The Identification of the parameters to be modelled is a delicate task due to the scarcity of proper experimental data and a large number of parameters. Stability problems are common in anaerobic digesters and these can be minimised or eliminated from the process by the use of appropriate strategies to control the process. These process control strategies involve the development of mathematical models, which represent the main processes that take place in the anaerobic digestion process. The power of models lies in their capacity in the following areas:

i) Identification of complex microbial communities and substrates in the Anaerobic Digestion process to identify the specific microorganism that makes a specific step efficient (Radhakrishnan & Mazumder, 2017).
ii) To predict the Kinetics of the digestion process, reactor stability, operation conditions, gas production, effluent quality, reactor process design and process mechanism (Radhakrishnan & Mazumder, 2017).

iii) Facilitates prediction of the amount of biogas yield in a fast-rate anaerobic treatment plant (Radhakrishnan & Mazumder, 2017).

iv) Model results can be used to demonstrate important inhibition patterns and suggest guidelines for optimal substrate mixing and operation of biogas reactors (Lima et al., 2016).

v) To identify appropriate models to be used for control and optimizing the anaerobic digestion process (Fedailaine et al., 2015).

vi) Mathematical models represent the anaerobic digestion process and this helps in understanding the process, predicting the system behaviour under varied conditions, formulation and validation of some hypotheses, the experimental information, calculating the costs of the biogas plant, estimation of the process risk and approximating time for the digestion process (Andres, et al., 2011).

vii) The modelling of microorganisms to be able to understand and predict the growth rate of anaerobic microbes in various operating conditions, impacts of antimicrobials in the digester and estimate the lag time (Ware & Power, 2017).

viii) According to Velusamy et al., (2020) methane production modelling predicts the kinetic parameters which help in monitoring the anaerobic digester performance under different conditions.

ix) Models assist farmers to assess whether anaerobic digestion is a financially viable venture for farm operations (Kythreotou et al., 2014).

x) Modelling of the anaerobic digestion process is of fundamental importance not only for the design of biogas plants but also to study the sensitivity of the plant behaviour to operational parameters, monitoring and controlling performance, and assessing the feasibility of the use of new substrates of varying characteristics, biodegradability and operational conditions (Elena, et al., 2012).

Biochemical Methane Potential (BMP) tests are lengthy, which could be reduced substantially if the final gas production could be predicted by the use of appropriate models. According to Andres, et al. (2011), the four principles for selecting a suitable model include:

(i) Predictive, the model should be applicable in the future and also in different conditions.

(ii) Simplicity, the model should be as easy to understand;

(iii) Identifiability, the unspecified parameters should be recognizable from the available data;

(iv) Causality, the model should represent the most relevant cause-effect relationships;

2.13.1 ANAEROBIC DIGESTION MODELS

Owing to the complexity of the Anaerobic Digestion process, the various models developed are for different uses, thus the variation of models depends on the purpose for which it was designed. Anaerobic digestion models have evolved since 1969. The initial models were relatively simple due to the limited knowledge about the process, further system analysis experimental investigation, and the increase in computing capacity led to the development of much more detailed models (Andres, et al., 2011). The anaerobic digestion model can be classified through evolution with time. The first anaerobic Digestion Model was developed in 1969, to simulate the stability of the anaerobic digester and predict the disturbances after a failed digestion process (Arzate, 2019). Anaerobic Digestion occurs in various steps, and one slower step is considered to control the rate of the entire process, the first models majored on the rate-limiting step of the process (Andres, et al., 2011). The rate-limiting step was the acetic acid degradation by bacteria.

According to Arzate (2019), the complexity of the models over the last 50 years could be represented as shown in Figure 2.10. According to Andres et al. (2011), the initial models focused on the rate-limiting step for the anaerobic digestion process which varies under different operating conditions. Various steps were considered to be rate-limiting, some considered methanogenesis and others hydrolysis. These models were simple to use but could not describe the process performance wholly, especially under different operating conditions. These were the models developed between 1969 to 1990. The most used model is the Anaerobic Digestion Model Number One (ADM 1). The ADM1 contained various phases explaining chemical and physical reactions. It included the four steps of anaerobic digestion (hydrolysis, acidogenesis, acetogenesis and methanogenesis) and the variation of these phases for substrates input. ADM1 is a bit complicated as it requires the input of numerous factors, though it is precise. This formed the basis of the formulation of other models by researchers. For this study, three Mathematical Kinetic models have been considered (Logistic, Modified Gompertz and First Order Kinetic models).

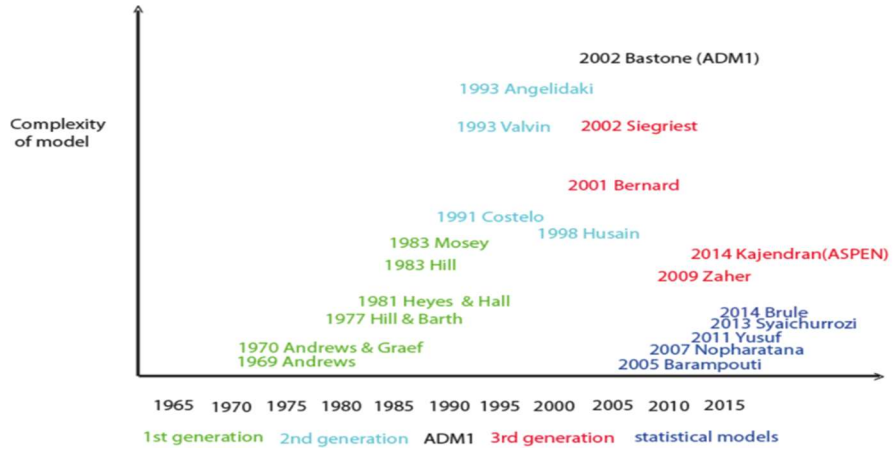

Figure 2.10: Evolution of Anaerobic Digestion models over the last fifty years.

2.13.2 FIRST-ORDER KINETIC MODEL

The first-order kinetic model is a simple model that assumes hydrolysis is the rate-limiting step in the anaerobic digestion process, it does not consider digester failures and the conditions to reach optimum biological activity. Researchers use this model to obtain hydrolysis kinetics with the help of batch anaerobic digestion data (Velusamy et al., 2020). According to Samuel et al. (2017), the production of methane follows the pattern of microorganisms and is characterised by an increasing and a decreasing limb expressed by linear and exponential equations. In addition, the First Order Kinetic model assumes the methane yield rate is proportional to the degradation of the substrate. After the digestion process, the residual organic component in the digester can be computed or predicted because the maximum methane yield is proportional to the degradation of the organic fraction of the substrate. The First Order Kinetic model requires less operational data and is simple to use thus often used for simulation of methane production. The first-order kinetic model is used in this study to predict the maximum methane yield and the rate constant.

The first-order reaction equation describes the utilization of limited substrate consumption as shown in equation 2.14 (Nweke & Nwaban, 2020).

$$\frac{-ds}{dt} = K_r S \qquad \text{Equation 2.14}$$

S = substrate concentration

t = hydraulic retention time (HRT)

Kr = first-order inactivation rate constant

The equation describes the microbial exponential growth. The concentration of the substrate can be written as the exponential biomass growth as the substrate is consumed. The substrate concentration of the influent is proportional to the substrate concentration of the effluent and the retention time used as seen in the equation.

According to Mohammad, et al. (2016), the first-order kinetic model assumes that the rate (R_S) which is the rate of substrate degradation is proportional to the amount of substrate present in the digester as shown by Equation 2.15.

$R_s = k\,X\,S_t$ Equation 2.15

k- First-order kinetics constant;

S_t - Amount of undegraded substrate remaining at time t (variable).

Integrating the degradation with the time yields the exponential equation 2.16 that gives the remaining substrate at time t (S_t).

$S_t = S\,X\,e^{-kt}$ Equation 2.16

S Total amount of degradable substrate;

k First-order kinetics constant;

t Time after experiment start-up.

From the batch anaerobic digestion kinetics, the cumulated methane yield produced at time t is as expressed by Equation 2.17.

$M_t = S\,X\,(1- e^{-kt})$ Equation 2.17

Equation 17 shows a model that is often used to describe batch anaerobic digestion. The First Order Kinetics model assumes that anaerobic digestion is a single-step process, but it takes place in four distinct steps. The First-order kinetics model as explained by Velusamy et al. (2020) is as shown by Equation 2.18

$Y(t) = Y(1 - \exp(-k.t))$ Equation 2.18

Y(t) = cumulative methane production (mL/g oDM)

Y =ultimate methane production potential (mL/g oDM)

t =time of day

k= first-order model constant (1/day)

2.13.3 MODIFIED GOMPERTZ MODEL

The modified Gompertz equation is an exponential model often applied to explain the digestion of simple organic substrates and estimate the methane yield kinetics. The degradation of simple substrates assumes the reverse L-shape curve shown in Figure 2.11 and with the complex substrates that have a high amount of fats the degradation pattern is not straightforward. The slow degradation of the fats and chances of acute inhibition bring about elongated S-shaped curves or stepped curves (Ware & Power, 2017).

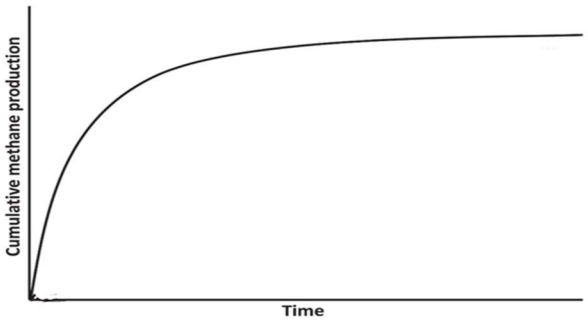

Figure 2.11: Cumulative methane yield curve for simple substrates (Ware & Power, 2017)

Gompertz model was used for organ growth prediction and human mortality data, it was later modified to describe the exponential rate of growth and lag phase period for cell density during the bacterial growth stage (Velusamy et al., 2020). The lag phase information from the model shows the minimum time the bacteria takes to acclimatize to the operating conditions and it also, shows the growth rate of methanogens. The biogas production rate is high when the growth rate is high (Velusamy et al., 2020; Ware & Power, 2017).

The Gompertz model equation describes the time taken for an anaerobic digestion process and implies there is no maximum cell growth rate (Borja et al., 2018). According to Velusamy et al. (2020), The Gompertz Model equation is as defined by Equation 2.19: -

$$Y(t) = Y.exp\left\{-\exp(Rm.\frac{e}{Y}\ (\lambda - t) + 1)\right\}$$ Equation 2.19

Y(t) = cumulative methane production (mL/g oDM)

Y =ultimate methane production potential (mL/g oDM)

Rm =maximum methane production rate (mL/g oDM/day)

t =time in days

e exp. (1) = 2.7183

λ = lag phase time (day)

2.13.4 LOGISTIC MODEL

Logistic models express the reaction rates of anaerobic digestion in a similar way to the simulation of population growth and also chemical intramolecular reactions. One of the simplest Logistic models that can be applied to the simulation of the biogas Process is the Verhulst equation (Mohammad, et al., 2016). The logistic model assumes that the amount of methane produced is proportional to the methane production rate and it gives an estimate of maximum methane production, the methane production potential of the substrate and the lag phase delay (Velusamy et al., 2020). According to Velusamy et al. (2020), The Logistic Model equation is as defined by Equation 2.20.

$$Y(t) = \frac{Y}{1+\exp\left(4\ X\ \frac{Rm(\lambda - t)}{(Y)}\right)+2}$$ Equation 2.20

Y(t) = cumulative methane production (mL/g oDM)

Y ultimate methane production potential (mL/g oDM)

Rm maximum methane production rate (mL/g oDM/day)

t time in days

e exp. (1) = 2.7183

λ lag phase time (day

CHAPTER THREE

3. MATERIALS AND METHODOLOGY

3.1 METHODOLOGY OVERVIEW

Batch Anaerobic Digestion was conducted with an inoculum and banana plant residues (stem, leaf and peduncle) as substrates. The results from the experiment were then used for kinetic modelling using the First Order kinetics model, Modified Gompertz model and Logistics Model to obtain the Kinetic parameters for the anaerobic digestion and optimization of the anaerobic digestion process.

3.2 SUBSTRATES AND INOCULUM (SEEDING SLUDGE)

The substrates used in this study were banana leaf (midrib and leaf blade), banana stem (leaf sheath) and banana peduncle as shown in Figures 3.1, 3.2 and 3.3. These were obtained from a farm and were stored frozen. The inoculum was untreated digested sludge per (DIN 38414-8, 1985) and was obtained from a wastewater treatment plant, more than a week before the experiment. The inoculum was stored at 37˚C in such a way that the sludge reduced most of its gas production and depleted the residual biodegradable organic material in it.

3.2.1 Characterization of substrate and inoculum

The characteristic parameters used in this study were consistency, and the substrates were all in a solid state. According to legal classification, as defined by (VDI-4630, 2006), the substrates were farm yard manure types. For the chemical composition, the dry matter Total solids (TS) and Organic Dry Matter content (oDM) was determined.

The solids content of the samples was determined according to the European standards (EN 12879, 2000) and (EN 12880, 2000). For determining the total solids (TS), samples with a certain weight were placed in ceramic petri dish and dried in an oven at 105°C for 24 hours until constant weight. The samples were then placed in the desiccators to cool, after cooling the samples were weighed for total solids. The samples were then burnt at 550°C for 2 hours in a furnace and let to cool off then the samples were weighed. The organic dry matter (oDM) was determined by subtraction of the minerals content of the sludge sample (residual ash after burning) from the total solids content. The formula for the calculation of total solids and organic dry matter was presented as Equations 3.1 and 3.2.

TS (g/Kg) = {(Wad-Wv)/ (Ws-Wv)} x 1000 Equation 3.1

oDM (%) = {(Wd-Wi)/ (Wd-Wv)} x 100 Equation 3.2

Wv = weight of empty vessel.

Ws =Weight of vessel with the sample.

Wd =Weight of vessel with the dried sample.

Wi =Weight of vessel with the ignited sample.

The substrates were prepared for the batch test by shredding them into smaller sizes as shown in Figures 3.1, 3.2 and 3.3. This was done to provide a large surface area for adsorbing the substrate that would result in increased microbial activity and hence increased gas production. The leaf was prepared by using the ratio of 30% midrib to 70% leaf blade, the midrib was shredded to a size of less than 10mm. The leaf blade already has a high surface area due to its broad shape thus it was shredded to a size slightly larger than the midrib but enough to pass through the batch test bottle with ease. The stem and peduncle were shredded to particle sizes of less than 10 mm.

Figure 3.1: Leaf midrib to the left, leaf blade in the middle, and a sample of leaf used in the batch test on the right.

Figure 3.2: Stem on the left and sample of the stem used in the batch test on the right.

Figure 3.3: Peduncle on the left and sample of peduncle used in the batch test on the right.

3.3 FERMENTATION BATCH TEST CRITERIA.

VDI 4630 (2016) is a German standard that provides rules and specifications for tests to determine the biogas output of organic materials. The experiment in this study was conducted following this standard. The (VDI-4630, 2016) sets criteria to be followed to achieve good results. The criteria followed in this study were as listed below.

3.3.1 Fermentation test apparatus

Glass material was used for all parts of the apparatus which were in contact with the biogas atmosphere and the equipment used was airtight. The internal pressure of the system influences the gas tightness of the equipment and also the solubility of the biogas components on the fermentation medium, therefore enough gas space above the level of the fermentation medium was provided, which will also enable the conversion of the measured pressure into gas volume. The experiment was set up in a constant temperature condition chamber.

3.3.2 Inoculum/seeding sludge

The inoculum had an organic dry matter content (oDM) greater than 50% of the solids content in accordance to (VDI-4630, 2006), and before the inoculum was used it was degassed, to ensure that its gas production levels had been sufficiently reduced.

3.3.3 Substrate

According to VDI-4630 (2006) to prevent inhibition in the fermentation batch, the ratio of oDM of the substrate to the oDM of the inoculum was kept at less than 0.5 as shown in Equation 3.3.

$$\frac{\mathrm{oDM}_{\mathrm{substrate}}}{\mathrm{oDM}_{\mathrm{seeding\ sludge}}} \leq 0.5 \qquad \text{Equation 3.3}$$

The gas yield from the substrate made up more than 80% of the total gas quantity of a sample. The fermentation batch-test composition is shown in Table 6.

3.3.4 Blank and controls

The seeding sludge/inoculum methane generation was determined in a blank assay with water only. The blank assay was carried out in triplicate for statistical significance (Angelidaki, et al., 2009).

3.3.5 Replicates

The number of replicates was three for each dilution and this allowed for accuracy and statistical analysis of the experimental data and guaranteed the reproducibility and replicability of the study assays.

3.3.6 Experimental design of fermentation batch composition.

The batch composition was as shown in Table 3.1. The gas volume was fixed for all reactors at 825mL before the experiment but due to variation of flask volume in the laboratory and the one chosen in the theoretical setting the gas volume varied in some batch setups.

Table 3.1: Composition of the batch test.

	0	1	2	3	4	5	6	7	8	9	10	11
	Stem	Stem	Stem	Leaf	Leaf	Leaf	Peduncle	Peduncle	Peduncle	Blank	Blank	Blank
Substrate oDM [g/kg]	47	47	47	207	207	207	68	68	68	17	17	17
Flask volume [mL]	1141.65	1134.02	1142.02	1114.55	1115.96	1116.26	1115.22	1116.37	1117.34	1160.79	1158.48	1157.79
Inoculum [g]	250	250	250	250	250	250	250	250	250	250	250	250
Substrate[g]	21.63	21.63	21.63	4.70	4.70	4.70	13.69	13.69	13.69	0	0	0
Water [mL]	39	37	37	36	36	38	27	27	29	83	83	83
Gas volume [mL]	831	825	833	824	825	824	825	825	825	828	825	825
oDM Inoculum [g]	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
oDM Substrate [g]	1.01	1.01	1.01	0.97	0.97	0.97	0.93	0.93	0.93	0.00	0.00	0.00
oDM Substrate / oDM Inoculum	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.00	0.00	0.00

TS - Dry matter Total Solids

oDM - Organic Dry Matter

3.4 EXPERIMENTAL SETUP

The apparatus was set up as shown in Figures 3.4 and 3.5 and the fermentation test was conducted following (VDI-4630, 2006). The gas volume was measured indirectly using a gas pressure measurement instrument per (DIN EN ISO 11734, 1998). The biogas produced was collected in the fermentation vessel.

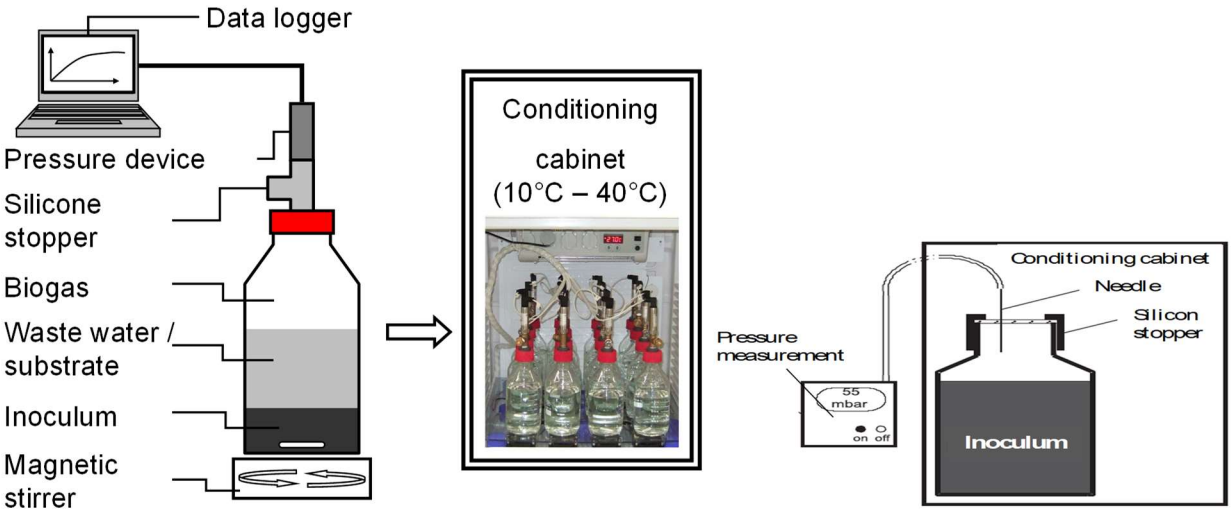

Figure 3.4: Experimental apparatus set up following DIN EN ISO 11734 (1998) (left), gas volume measurement by a semi-technical test facility with pressure transmitters directly attached to the bottleneck but without a hose line (right) (Meier et al., 2009).

Figure 3.5: Experimental setup in the laboratory

3.5 TEST PROCEDURES.

Batch fermentation was carried out in triple determinations; this also applied to the blank sample. First, the samples of leaf, peduncle and Pseudo stem were shredded into small pieces to have a high surface area for the substrate thus enhancing the bacterial degradation. The required amount of each substrate was then weighed into triplicate and then put carefully into the fermentation vessel. Water was measured and fed into the fermentation vessels, then followed by the seeding sludge. The blank was fed with an equivalent amount of water instead of substrate.

Before closing the fermentation vessels, the gas phase was flushed with nitrogen for 10 seconds to remove residual oxygen from the gas phase. The vessels were then immediately sealed and put into the fermentation chamber, which was set up at a temperature of 37 ˚C. This temperature was maintained throughout the experiment; thus, the fermentation batch test was carried out at mesophilic temperature.

The volume of the biogas produced was measured indirectly by a pressure measurement instrument. The gas pressure was automatically recorded after every five minutes. The test continued until the gas pressure changes reduced sufficiently to levels that showed there was very little or no further gas production. The recorded gas pressures after the experiment were then collected and analysed to quantify the amount of gas produced. The analysis that was done with regards to the anaerobic batch test, included calculations of the total volume of gas collected, gas produced from the substrates and Methane gas produced. These calculations are as follows:-

i) The total volume of gas produced

The gas (Biogas) volume was calculated by the formula in Equation 3.4.

Biogas Produced (mL) = (P x Vh x 273.15)/ (273.15+T) x1.01325 Equation 3.4

P=Gas pressure in the reactor vessel in bars

T=Gas temperature at ^{0}C

Vh=Volume of headspace in the reactor

1.01325= standard pressure in bars

273.15 = conversion factor added to the temperature at ^{0}C to convert to Kelvins.

Since the experiment was done in triplicates, the average values were then used for each substrate.

ii) Gas produced from substrates ($V_{substrate}$)

The actual volume produced from the substrates was calculated using Equation 3.5.

$V_{substrate} = V_{Total} - V_{Sludge}$ Equation 3.5

V_{Total}= Total biogas produced

V_{Sludge} = volume of gas produced by the sludge.

iii) Methane produced

Once the gas composition was determined, then the percentage of methane produced was calculated by Equation 3.6.

Methane gas produced = $V_{substrate\ x}$ (% of the methane from gas analysis) Equation 3.6

A precaution in the running of the test was to ensure that the gas pressure in the fermentation vessel did not exceed 1.8 bars, when this was reached the gas was released to avoid bottle breakage. The fermentation material was also regularly mixed with a magnetic stirrer as shown in Figure 3.4. After the batch test was complete, the pH of the fermentation residue was measured electrochemically using a pH meter. The COD of the residue (both Solid and liquid) was also determined. The gas produced was subjected to further tests to determine its composition.

3.6 KINETICS STUDY AND STATISTICAL ANALYSIS

Kinetic modelling of the methane yield is used to optimize and predict kinetic parameters which are used for monitoring and predicting the performance of the anaerobic reactor under various operating conditions. The models used here are the First Order Kinetics Model (Equation 27), Modified Gompertz model (Equation 28), and Logistic Model (Equation 29). These models were used to fit the cumulative Methane data obtained from the Anaerobic batch tests. Microsoft Excel 2019 nonlinear regression was used to simulate the first-order kinetic model and the kinetic parameters: that is the first-order disintegration rate constant (k) and predicted methane yield (Y) were obtained by using the solver tool for Excel. The statistical software, IBM SPSS Statistics 20, was used for simulating and predicting the kinetic parameters (Rm maximum biogas production rate, λ lag phase time and Y predicted Methane yield) for Modified Gompertz and Logistic models.

The equations for the Kinetic models used in the simulations are as shown in Equations 3.7, 3.8, and 3.9 respectively.

$$Y\ Y(t) = Y \times [1 - \exp(kt)] \quad \text{Equation 3.7}$$

$$Y(t) = Y \times exp\left\{-\exp\left(\frac{Rm \times e}{Y}(\lambda - t) + 1\right)\right\} \quad \text{Equation 3.8}$$

$$Y(t) = \frac{Y}{1+exp\left\{4\ X\ \frac{Rm \times(\lambda - t)}{Y} + 2\right\}} \quad \text{Equation 3.9}$$

Where,

Y(t) = cumulative methane production (mL/g oDM)

Y= ultimate methane production potential (mL/g oDM)

t= time in day

k = first-order model constant (1/day)

Rm = maximum methane production rate (mL/g oDM /day)

e = 2.7183

λ= lag phase time (day)

The best-fitting model is the suitable one to predict the efficiency of an anaerobic digestion reactor and also analyse the mechanisms and metabolism involved in the Anaerobic digestion of banana plant residues. Since each of the models has its strengths and weaknesses, to obtain the best fit model, the coefficient of determination (R^2) and root mean square error (RMSE) were calculated for each model. R^2 was calculated using Microsoft Excel 2019 for the First Order Kinetic model and statistical software, IBM SPSS Statistics 20 for Gompertz and Logistic Models. The root mean square error (RMSE) measures the differences between the model prediction and the values observed; it was calculated using Equation 3.10. The model with lower values of RMSE showed the best fit.

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}i - yi)^2}{n}} \quad \text{Equation 3.10}$$

Where

ŷi is the model result

yi is the experimental result

n is the data number

CHAPTER FOUR

4. ANAEROBIC DIGESTION RESULTS AND DISCUSSION

4.1 TOTAL SOLIDS AND ORGANIC DRY MATTER

The values for total solids and organic dry matter were calculated from Equation 21 and Equation 22 as shown in Table 4.1.

Table 4.1: Total solids and Organic dry matter results and calculations.

Substrate	Wv (g)	Ws(g)	Wd(g)	TS (g)	TS (%)	TS (g/kg)	Wi(g)	oDM (%)
Stem	42.50	46.50	42.70	0.20	5.00	50.00	42.51	93.48
Leaf	48.60	51.20	49.20	0.60	23.08	230.77	48.66	89.61
Peduncle	41.50	45.30	41.80	0.30	7.89	78.95	41.54	85.71

Wv = weight of empty vessel.

Ws =Weight of vessel with the sample.

Wd =Weight of vessel with the dried sample.

Wi =Weight of vessel with the ignited sample.

TS= Total solids.

oDM = Organic dry matter.

The substrates (stem, leaf and peduncle) all had high organic dry matter. From the experiment setting in Table 3.1, the ratio of oDM substrate to oDM inoculum was less than 0.5 for all, thus there was minimal inhibition. The inoculums used had total solids of 56.42 g/kg and organic solids of 72.49%, thus its organic dry matter content was greater than 50% of the solid contents hence the inoculum had sufficient microbial biomass for fermentation. The organic dry matter comprises the biodegradable organic dry matter fraction and the Refractory organic dry matter. Knowledge of the Biodegradable organic dry matter fraction of the substrate helps in the estimation of the biodegradability of substrate and estimation of biogas generation. Lignin is a complex organic polymer that is hard to digest and contains refractory organic dry matter. The feedstock composition affects the biogas quality, biogas yield and digestate quality. The banana plant

residues are characterized by high quantities of degradable mater and high oDM best suited to anaerobic digestion treatment (Chaudhary, 2008).

4.2 CHEMICAL OXYGEN DEMAND (COD)

During COD tests both organic and inorganic components are oxidized and the required COD is the one from the organic component of the substrate. In this study, COD is calculated rather than measured due to the high consumption of expensive chemicals, such as catalysts and toxic metals to prevent the interference of halide anions during the process of measuring it. COD of a substrate can be calculated from the fraction of carbohydrates, proteins and lipids in the substrate. For carbohydrates, the COD can be calculated from the concentration of the oxidizable compound in the sample, based on its stoichiometric reaction with oxygen to yield CO_2 (assume all carbon becomes carbon dioxide), water (assume all hydrogen becomes water) and ammonia (assume all nitrogen becomes Ammonia), using Equation 4.1. Proteins have an average value of COD of 1.2g $_{Oxygen}$ g^{-1} oDM while for lipids the average value is 2.6 g $_{Oxygen}$ g^{-1} oDM (Rojas et al., 2011).

$$COD = (C/FW) \times (RMO) \times (32) \quad \text{Equation 4.1}$$

C = Concentration of oxidizable compound in the sample.

FW = Formula weight of the oxidizable compound in the sample.

RMO = Ratio of the number of moles of oxygen to several moles of oxidizable compounds in their reaction to carbon dioxide, water, and ammonia.

Thus, to get the COD of the substrate, Equation 4.2 is used.

$$COD_{\text{degradable substrate}} = f_{CH}\, COD_{\text{Carbohydrates}} + f_{PR}\, COD_{\text{Proteins}} + f_{LI}\, COD_{\text{Lipids}} \quad \text{Equation 4.2}$$

f_{CH} = fraction of carbohydrates

f_{PR} = fraction of Proteins.

f_{LI} = fraction of lipids. (Rojas, Uhlenhut, Shlaak, Borchert, & Steinigeweg, 2011)

Substrates used included: -

i) Banana leaf (70% leaf blade and 30% midrib)
ii) Banana stem (leaf sheath)
iii) Banana peduncle. (floral Stalk)

Summarising the values in Tables 2.5 and 2.6 gives the results presented in Table 4.2.

Table 4.2: Chemical composition for COD calculations.

	Stem (%)	Leaf (%)	Peduncle (%)
Lignin ($C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$)	9.37	18.27	9.70
Cellulose($C_6H_6O_5$)	26.27	18.70	14.23
Holocellulose($C_6H_6O_5$)	35.00	32.38	18.40
Pentosans($C_5H_4O_5$)	8.73	10.63	7.25
Starch($C_6H_{10}O_5$)	5.92	0.74	23.84
Proteins	1.34	5.28	2.90

Lignin, cellulose, hollo cellulose, pentosans, and starch are all carbohydrates. Their COD is calculated assuming the concentration of the oxidizable compound in the sample is $1g_{substance}\ g^{-1}$oDM. The calculations were as follows:

i) Lignin

$C_9H_{10}O_2 + 91/2\ O_2 \rightarrow 9CO_2 + 5\ H_2O$ Equation 4.3

$COD_{Lignin} = (1g_{Lignin}\ g^{-1}oDM\ /150\ mol_{Lignin})\ (9.5\ mol\ O_2/\ 1\ mol_{Lignin})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 2.03\ g_{Oxygen}\ g^{-1}\ oDM$

$C_{10}H_{12}O_3 + 11\ 1/2\ O_2 \rightarrow 10CO_2 + 6\ H_2O$ Equation 4.4

$COD_{Lignin} = (1g_{Lignin}\ g^{-1}oDM\ /180\ mol_{Lignin})\ (11.5mol\ O_2/\ 1\ mol_{Lignin})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 2.04\ g_{Oxygen}\ g^{-1}\ oDM$

$C_{11}H_{14}O_4 + 12\ 1/2\ O_2 \rightarrow 11CO_2 + 7\ H_2O$ Equation 4.5

$COD_{Lignin} = (1g_{Lignin}\ g^{-1}oDM\ /210\ mol_{Lignin})\ (12.5\ mol\ O_2/\ 1\ mol_{Lignin})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 1.75\ g_{Oxygen}\ g^{-1}\ oDM$

COD_{Lignin} Average $= (2.03\ g_{Oxygen}\ g^{-1}\ oDM + 2.04\ g_{Oxygen}\ g^{-1}\ oDM + 1.75\ g_{Oxygen}\ g^{-1}\ oDM) / 3$

$= 1.94\ g_{Oxygen}\ g^{-1}\ oDM$

ii) Cellulose

$C_6H_6O_5 + 5\ O_2 \rightarrow 6CO_2 + 3\ H_2O$ Equation 4.6

$COD_{Cellulose} = (1g_{cellulose}\ g^{-1}oDM\ /158\ mol_{cellulose})\ (5\ mol\ O_2/1\ mol_{cellulose})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 1.01\ g_{Oxygen}\ g^{-1}\ oDM$

iii) Holocellulose

$C_6H_6O_5 + 5\ O_2 \rightarrow 6CO_2 + 3\ H_2O$ Equation 4.7

$COD_{Holocellulose}$

$= (1g_{Holoellulose}\ g^{-1}oDM/158\ mol_{Holocellulose})\ (5\ mol\ O_2/1\ mol_{Holocellulose})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 1.01\ g_{Oxygen}\ g^{-1}\ oDM$

iv) Pentosans

$C_5H_4O_5 + 31/2\ O_2 \rightarrow 5CO_2 + 2\ H_2O$ .....Equation 4.8

$COD_{Pentosan}$

$= (1g_{Pentosan}\ g^{-1}oDM\ /164\ mol_{pentosan})\ (3.5\ mol\ O_2/1\ mol_{pentosan})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 0.68\ g_{Oxygen}\ g^{-1}\ oDM$

v) Starch

$C_6H_{10}O_5 + 6\ O_2 \rightarrow 6C\ O_2 + 5\ H_2O$ .....Equation 4.9

COD_{Starch}

$= (1g_{Starch}\ g^{-1}oDM\ /162\ mol_{starch})\ (6\ mol\ O_2/1\ mol_{Starch})\ (32\ g\ mol^{-1}\ O_2/\ 1\ mol\ O_2)$

$= 1.19\ g_{Oxygen}\ g^{-1}\ oDM$

Calculation of the various substrates COD using Equation 22 gives the results in Table 4.3

Table 4.3: Calculated COD for the various substrates.

	COD Stem ($g\ O_2\ g^{-1}oDM$)	COD Leaf ($g\ O2\ g^{-1}oDM$)	COD Peduncle ($g\ O2\ g^{-1}oDM$)
Lignin	0.18	0.35	0.19
Cellulose	0.27	0.19	0.14
Holocellulose	0.35	0.33	0.19
Pentosans	0.06	0.07	0.05
Starch	0.07	0.01	0.28
Proteins	0.02	0.06	0.03
Total COD	0.95	1.01	0.89

The COD for the inoculum used is 28,000mgO_2/l. For the batch test, the COD values were as shown in Table 4.4.

Table 4.4: COD values for the anaerobic digestion.

Component	COD Value
Stem	47.5(g/Kg)
Leaf	236.9(g/Kg)
Peduncle	70.3(g/Kg)
Inoculum	7,000mgO_2/L per flask

The COD for the liquid digestate after the batch test is shown in Table 4.5.

Table 4.5: COD values after anaerobic digestion.

Component	COD with inoculum (g/L)	COD without inoculum (g/L)
Stem	14.3	-
Leaf	23.2	3.9
Peduncle	21.5	2.2
Inoculum	19.3	-

Table 4.5 shows the COD values in the digester after the anaerobic digestion considerable removal efficiencies of COD were observed. The COD removal efficiencies for all the samples are comparable to those reported in the literature from various studies. The COD removal efficiencies range from 60 to 75%. The high efficiency of removal of COD is an indicator that anaerobic digestion can be used for the stabilization of the digestate before using it as hummus fertilizer.

4.3 pH

The pH after the batch test was measured as shown in Table 4.6. The microbial metabolism is influenced by pH variations in the digester. At pH greater than 5 the efficiency for methanogenesis is high and a high rate for methanogenesis is at a neutral range of pH. A greater number of anaerobic bacteria including methanogens perform well in a pH range of 6.5 to 7.5, and the rate of

methane yield decreases in pH of less than 6.3 and more than 7.8. The resulting pH after the anaerobic digestion shows the digest had a suitable pH for use as a fertilizer.

Table 4.6: pH values after the batch test

	pH
Stem	7.56
Leaf	7.58
Peduncle	7.64
Inoculum	7.84

4.4 BIOGAS YIELD

The biogas yield for the blanks on average was as shown in Figure 4.1, indicating that the inoculum had no inhibition and was substantially degassed. The biogas produced in Figure 4.1 was subtracted from the average total volume of biogas produced for each substrate to get Figure 4.2.

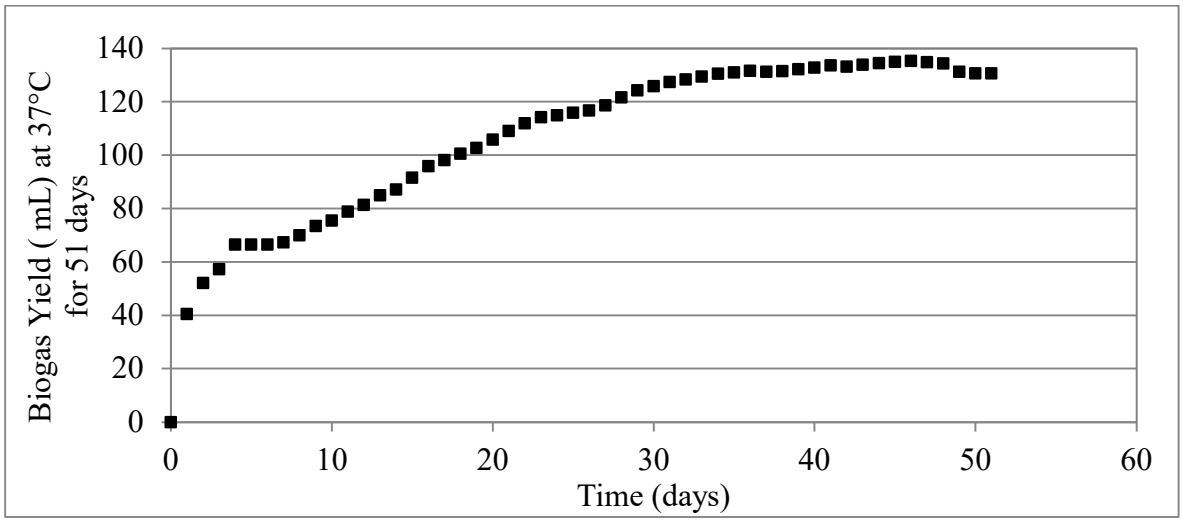

Figure 4.1: Biogas average yield for the blank.

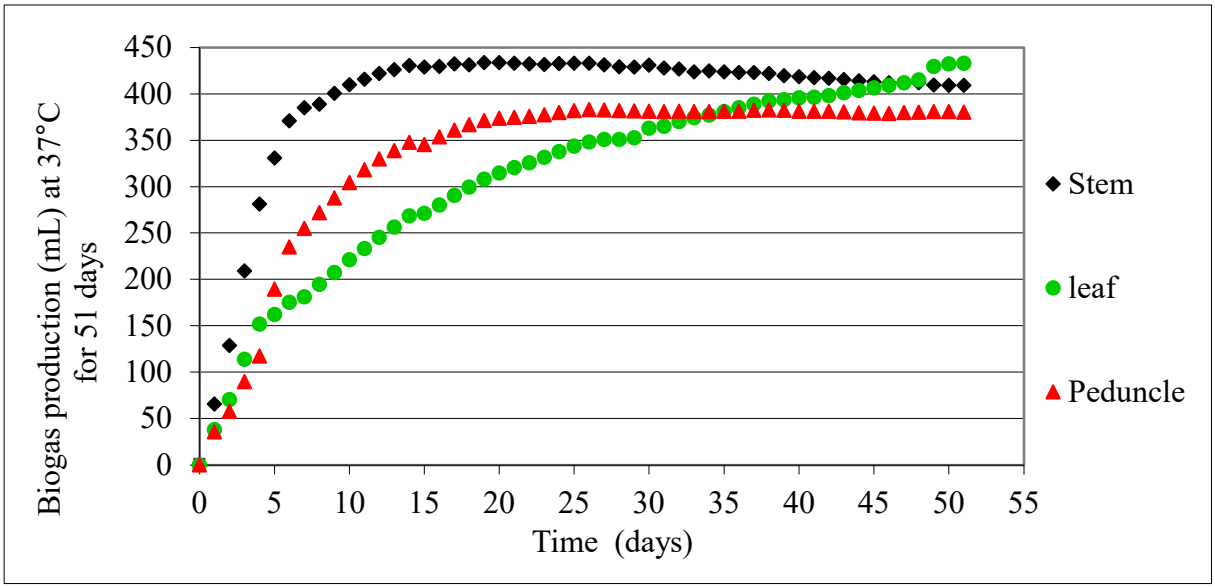

Figure 4.2: Cumulative Net biogas for the substrates.

The net biogas produced by the three substrates was as shown in Figure 4.2. According to (VDI-4630, 2006), the stem and the peduncle showed a normal curve for degradation but the leaf had a retarded degradation curve. The stem and the peduncle degraded with ease as compared to the leaf which took time to degrade (Slowly degradable), that even after the 51 days of the experiment it was still being degraded, though the gas production was very little. The stem and the peduncle were substantially reduced in quantity and appearance as compared to the leaf, whereby the blades were almost similar to, the leaf substrate at the beginning, though, the midrib was not identifiable after degradation as seen in Figure 4.3.

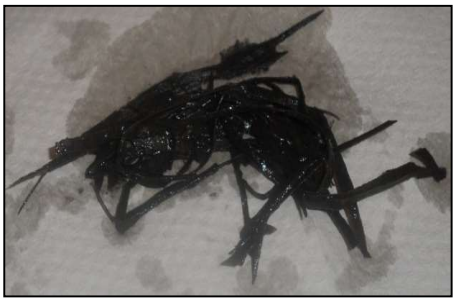

Figure 4.3: Leaf substrate after the batch test.

It is thus, evident that the leaf is comprised of a higher percentage of lignin material as compared to the other substrates, and lignin is generally inhibitive to enzymatic hydrolysis and this made the leaf to be hardly degradable anaerobically.

The high composition of lignin by a substrate indicates slow degradation, resistance to chemical and enzymatic degradation and lower methane potential of substrates. Lignin offers a natural defence of plants against microbial attacks thus the necessity for the breakdown of the lignocellulosic compound by pre-treating the substrate. Pre-treatments alter the structure and composition of the substrate to remove or minimise the inhibition and thus, improve the rate of hydrolysis. Effective pre-treatment methods decrease cellulose crystalline nature, solubilize hemicellulose releasing sugars, increase the specific surface area, and increase the ease of access of enzymes for hydrolysis without generation of inhibitors and substrate loss.

4.5 METHANE YIELD

Analysis of the biogas produced by gas chromatography as shown in Appendix 1 enabled one to get the methane part of the gas. The methane quantity produced for the various substrates was shown in Table 4.7 and Figure 4.4. Biogas normally burns if there is more than 45% of methane but from the experiment, none of the substrates produced gas with this amount; all were less than 45%. This can be attributed to nitrogen that was used for flushing the bottle at the beginning of the experiment as is shown in Appendix 8.1, where the air (nitrogen and Oxygen gases) has the most percentage. Recalculating this to an upscale plant we get the methane and carbon dioxide ratios as shown in Table 4.7. The gas quality was good as there was very little ammonia and hydrogen sulphide produced.

Table 4.7: Methane gas produced in the laboratory and recalculated methane and carbon dioxide percentages in the upscale plants.

	% Methane in laboratory	% Methane in upscale plant	% Carbon dioxide in upscale plant
Stem	29	67.6	32.4
Leaf	14	65.3	34.7
peduncle	32	68.8	31.2
Blank	12	59.2	40.7

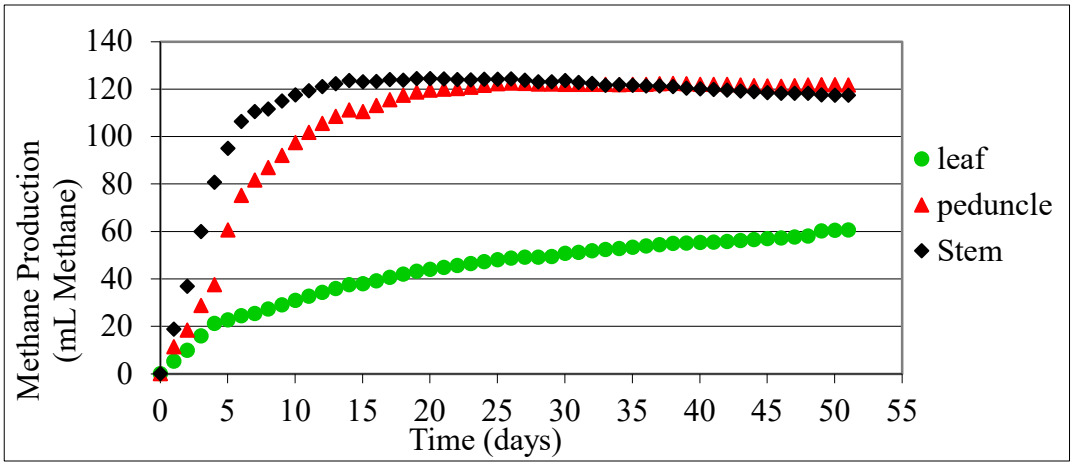

Figure 4.4: Cumulative Methane yield for the substrates

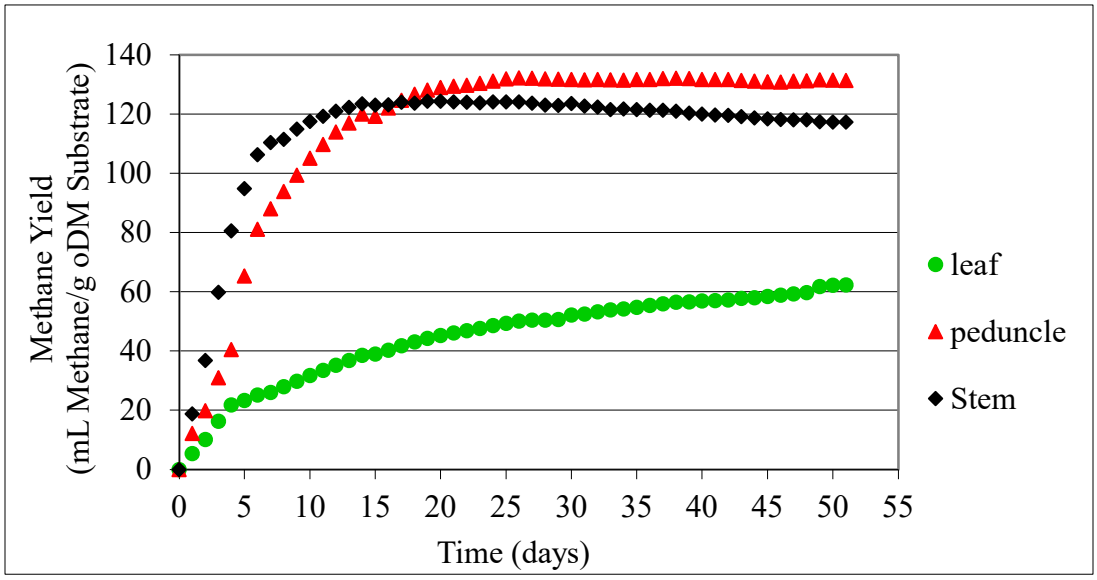

Figure 4.5: Methane yield for the substrates per gram oDM

The methane yield was as shown in Figure 4.5. The stem had a maximum methane yield of 124.45mL/goDM. This can be compared to the results from (Khan, Maurer, Argyropoulos, Mathieu, & Mueller, 2009) which was found to be 0.256 m^3CH4/kg oDM at a retention time of 35 days, thus the results obtained were half as much as those from (Khan et al., 2009). One reason for the difference was the composition of the stem used by (Khan et al., 2009) was both the leaf sheaths (pseudo stem) and flower stalk (peduncle) in this study the yield was 256.78 mL /g oDM of Methane (124.45 mL/g oDM +132.33 mL/g oDM) with a retention time of 35 days. The difference in methane production is also attributed to the nature of pre-treatment and storage of the substrate

as explained by (Kalia et al., 2000). Banana stem, due to its fibrous nature, is not very favourable for good methanogenesis. Various pre-treatment methods are required to break down the fibrous nature as was the case in (Kalia et al., 2000), the relatively higher yields could be due to the pre-treatment and temperature employed. The Peduncle produced 132.33 mL/ g oDM of methane for 51 days; when fibrous residues are used the bacterial population needs time to adjust before being able to degrade the fibre component efficiently. There is not so much literature on the biodegradation of the peduncle alone. Like in (Clarke et al., 2008), the study used both waste green bananas and peduncles of which the methane yield was $0.398 m^3 CH_4$/kg oDM.

Banana leaves used in this study were 30% midrib and 70% leaf blade and they produced 62.34mL/g oDM of methane. This is low, compared to the peduncle and the stem. (Mandal & Mandal, 1997) reported the value of biogas from banana leaves to be $0.0018 m^3$ biogas with a retention time of 90 days and from this study, the biogas value was 445mL of biogas which is comparable. The leaves are slowly degraded as even after the 51 days there was still some gas, though little was being produced. This was explained by (Reddy et al. (2010), that a high concentration of lignin and hemicelluloses, limits the cellulose available for digestion by the microorganisms. As explained by Velusamy et al. (2020) lignin bonds with hemicelluloses and celluloses making it a complex structure that has three phenyl-propane precursor monomers that are hard to degrade. Lignin forms a barrier to the hemicellulose and cellulose compounds making it difficult to access these compounds for digestion and this results in a slow hydrolysis process and low degradation efficiency of lignocellulosic biomass.

Hemicellulose and lignin are complex polymers and are difficult to degrade by anaerobic bacteria hence pre-treatments of the banana leaf increase the surface area of cellulose exposed to bacteria for degradation. This is done by destroying the cell wall to remove the lignin seal and exposing the fibres, solubilizing hemicellulose, and disrupting the crystallinity of the cellulose. For good yields pre-treatment of cellulosic biomass like acid treatment, alkali treatment and also dried banana leaves are used. The value of methane produced from a banana plant residue is shown in Table 4.8.

The theoretical methane yield from each substrate was as shown in Table 4.9; this is calculated considering 1g of COD has 350mL of Methane. The laboratory methane yield per gram of COD is shown in Figure 4.6 and Table 4.9. The theoretical gas value was almost 2.7 and 2.5 times greater for the stem and peduncle respectively. The theoretical gas value normally represents the upper limit which in practical cases is not achievable due to varied operating conditions and also technical restrictions (Fischer, et al., 2010). For the leaf the theoretical value was 6.5 times that achieved in the laboratory, this, other than the theoretical value being an upper limit, clearly shows that the leaf has very high lignin components that are an inhibition that hinders it from producing the desired gas levels. The biodegradability rate was calculated as the ratio of the experimental methane yield to the ratio of the Theoretical methane yield.

Table 4.8: Methane yield from various components of banana waste.

Component	Methane Yield (m^3CH4/kg oDM)
Stem	0.125
Peduncle	0.132
Leaf	0.062

Table 4.9: Theoretical and laboratory methane yield from COD of substrate

	COD (g)	Theoretical Methane Yield (mL)	Laboratory Methane Yield (mL)	Biodegradability rate (%)
Stem	0.95	332.5	122	36.7
Leaf	1.01	353.5	54	15.3
Peduncle	0.89	311.5	127	40.8

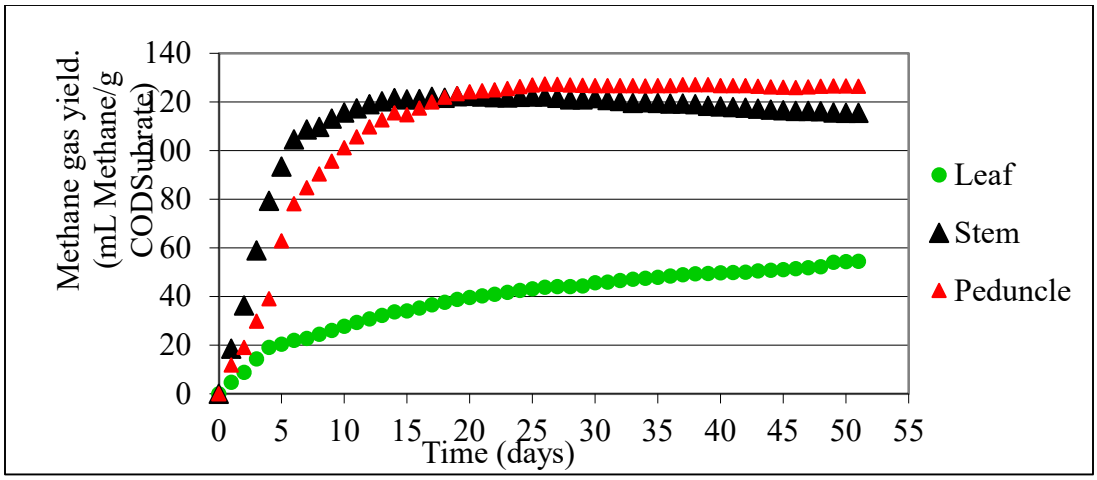

Figure 4.6: Laboratory Methane Yield per gram COD

4.6 DIGESTATE

4.6.1 Solid Residue

The digestate from banana plant residues has desirable qualities as compost, since it does not contain heavy metals contamination, plastic or glasses and has desirable nutrients. The pH is shown in Table 4.6 and is within the desired range. The solid residue can have its particle size reduced to be used as a soil conditioner or coarsely shredded for mulching. Salt properties of the solid residue include nitrogen, potassium, calcium, sulphur, magnesium, and phosphorus (Clarke et al., 2008).

4.6.2 Liquid Residue

The banana plant residues have high moisture content and thus high liquid content that remains after digestion. The liquid residue was evaluated for COD as is shown in Table 14 and it ranges from 2000mg/L to 4000mg/L. Other nutrients were not measured but from the study of (Clarke et al., 2008), it was found that the liquid digestate has a high content of Potassium (≈4200 mg/L). These nutrients, therefore, are in excess and have the potential of leaching, thus treatment of the nutrients is recommended.

CHAPTER FIVE

5. KINETIC MODELLING OF METHANE YIELDS FROM ANAEROBIC DIGESTION RESULTS AND DISCUSSIONS

5.1 KINETIC ANALYSIS AND MODEL SELECTION

Kinetic modelling of methane production demonstrates the substrate behaviour under various conditions in the anaerobic digester, Further, when designing a full-scale anaerobic digester, the results of kinetic modelling of methane production help to design, size, and optimize the digester in comparison with the obtained experimental yields. This study used Modified Gompertz, First Order Kinetic, and Logistic models to obtain the methane production Kinetics. The results of the kinetic modelling are presented in Table 5.1 and Figures 5.1, 5.2 and 5.3. All three models show a good fit with the experimental data. To get the most accurate model, the values of R^2 and RMSE were evaluated. The R^2 was high for the Modified Gompertz Model and the RMSE was the lowest signifying that it is the most robust model for maximum/ ultimate Methane Yield. This was also observed by (Zubayeda Zahana, 2017). The predicted methane yield difference from the experimental methane yield was also low with values below 10% which also showed that the Modified Gompertz Model was most suitable for methane yield prediction.

The hydrolysis rate (k) from the first Kinetic order model was found to range between 0.09 to 0.21 per day, generally, a higher value of k denotes faster degradation. For this case, the hydrolysis was not so fast because of the lignin and hemicellulose components of the substrates, whereby these bonds have to be broken fast before degradation takes place hence the low values of k.

The maximum methane rate production (Rm) as shown by both Modified Gompertz and Logistic models shows that the substrates used were degradable. The lag phase (**λ**) for the stem and the peduncle for both models was low as compared to one of the leaves. According to (Sagor Kumar Pramanik, 2019) a high λ value could reduce the adaptation ability of microorganisms to the reaction system and produce biogas within a longer timeframe.

The Modified Gompertz model was suitable as it had high R^2 values and low RMSE values for all the substrates thus, the Modified Gompertz model is best suited to predict the kinetics of the

Anaerobic Digestion process and optimize the process parameters, thus improving the design and operations of the Anaerobic digestion process. This then justifies the hypothesis that exponential models in this case Modified Gompertz model best explain the kinetics of slowly degradable lignocellulosic substrates.

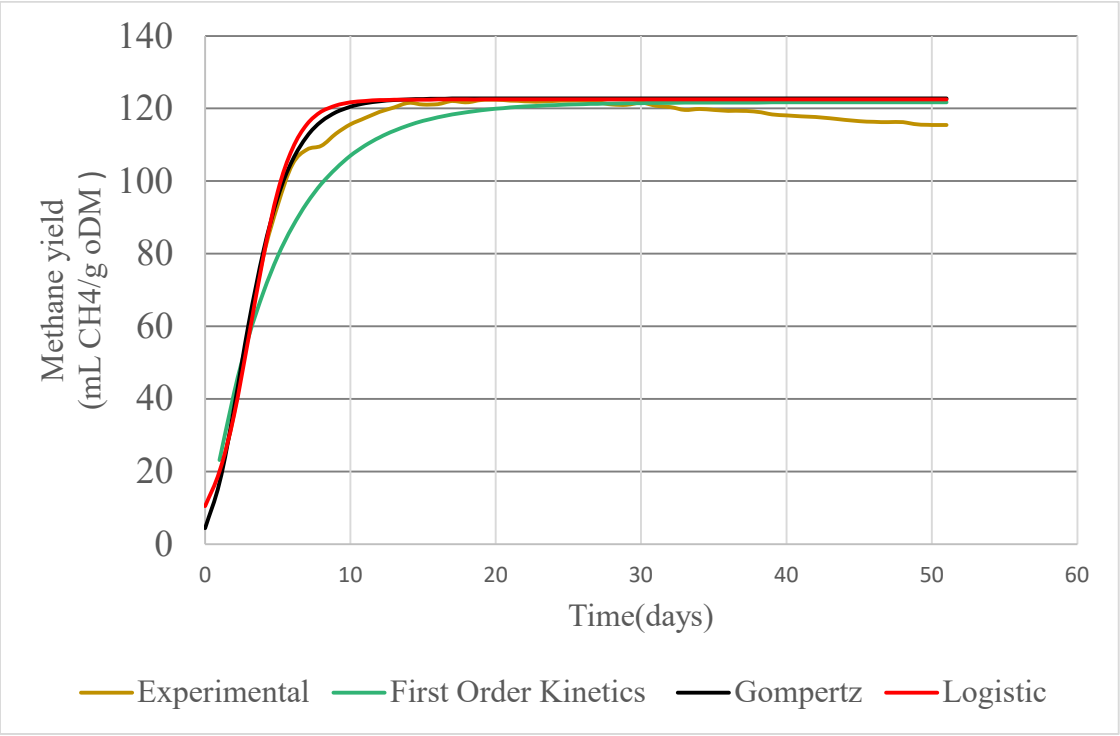

Figure 5.1: Profile of measured and predicted methane yield for stem

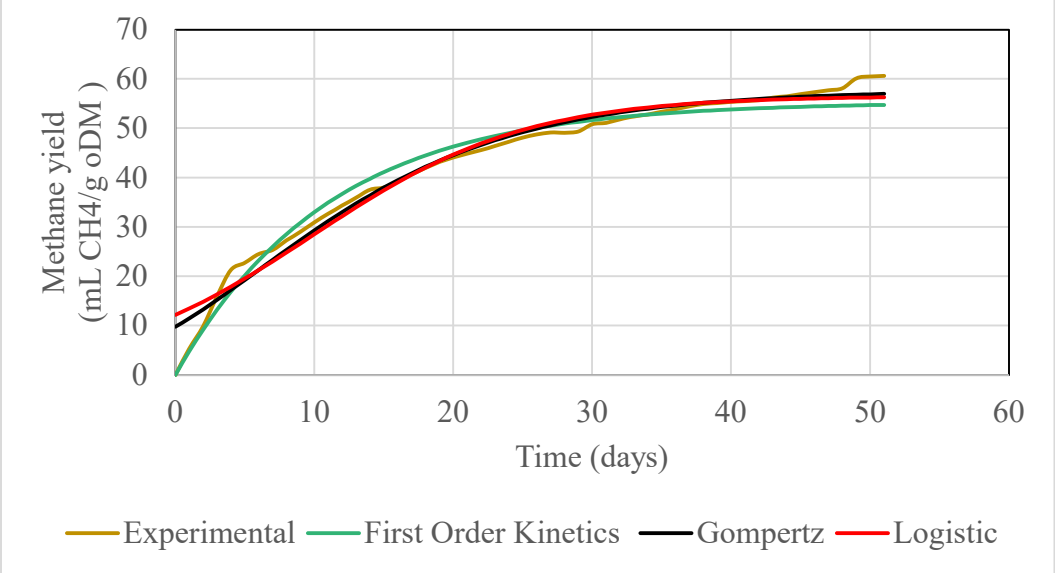

Figure 5.2: Profile of measured and predicted methane for leaf

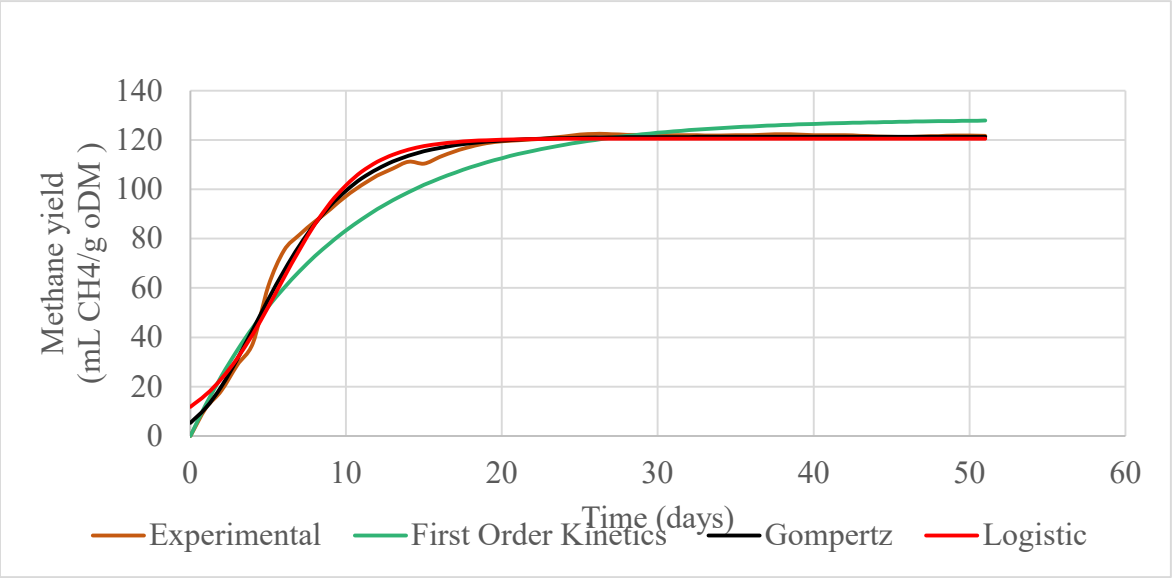

Figure 5.3: Profile of measured and predicted methane for Peduncle

Table 5.1: Estimated kinetic parameters for First Order Kinetic, Modified Gompertz and Logistic Models.

First Order Kinetics Model							
Substrate		Hydrolysis rate constant (1/day)	R square	RMSE	Predicted methane yield ($mL/CH_4/g$ oDM)	Measured methane yield ($mL/CH_4/g$ oDM)	The difference in methane yield (%)
Stem		0.21	0.925	5.886	121.72	125	2.7
Leaf		0.091	0.969	2.427	55.29	62	12.1
Peduncle		0.10	0.94	7.511	129	132	2.33
Modified Gompertz Model							
Substrate	Lag phase (λ) (days)	Maximum Methane production rate (Rm) ($mL/CH_4/g$ oDM)	R square	RMSE	Predicted methane yield ($mL/CH_4/g$ oDM)	Measured methane yield ($mL/CH_4/g$ oDM)	The difference in methane yield (%)
Stem	0.384	23.322	0.992	2.293	122.82	125	1.77
Leaf	4.392	2.048	0.974	2.382	57.00	62	8.77
Peduncle	0.496	12.314	0.994	2.340	121.349	132	8.78
Logistic Model							
Substrate	Lag phase (λ) (days)	Maximum Methane production rate (Rm) (mL CH_4/g oDM)	R square	RMSE	Predicted methane yield ($mL/CH_4/g$ oDM)	Measured methane yield ($mL/CH_4/g$ oDM)	The difference in methane yield (%)
Stem	0.496	22.739	0.987	2.938	122.486	125	2.05
Leaf	5.407	1.849	0.963	2.930	56.55	62	9.64
Peduncle	0.550	11.763	0.985	3.759	120.634	132	9.42

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSIONS

Anaerobic batch tests performed under mesophilic conditions conclusions can be drawn which include;

i) The methane yields and duration of anaerobic digestion were determined, the banana plant residues all have hemicellulose and lignin in their structure thus making them slowly degradable and the methane yields were 0.125, 0.132, and 0.062 m^3CH4/kg oDM for the stem, peduncle and leaf respectively for 51 days.

ii) The quality of biogas produced from the batch anaerobic digestion of the banana plant residues was of good quality as it had more methane as compared to carbon dioxide gas, the methane yield was 68%,65% and 69% for the stem, leaves and peduncle respectively.

iii) The biodegradability rate as per the experimental methane yield compared to the theoretical methane yield were 36.7%, 15.3% and 40.8 % for the stem, leaf and peduncle respectively.

iv) The biodegradability rate shows that the substrates have a potential for methane yield and this yield can be enhanced through favourable pre-treatment of these substrates that have lignin, hemicellulose and cellulose.

v) The kinetic modelling done concluded the Modified Gompertz model best describes the anaerobic digestion of the various banana plant residues as it had high R^2 values and low RMSE values for all the substrates. The values for R^2 were 0.992,0.974 and 0.994 for stem, leaf and peduncle respectively and The RMSE values were 2.293,2.382 and 2.342 for the stem, leaf and peduncle respectively.

vi) The digestate produced after digestion of banana plant residues was found to be favourable for use in the farm in quality as it had desired nutrients to the soil and minimum harmful or toxic components to the soil.

6.2 RECOMMENDATIONS

From the study, it is recommended that the Anaerobic digestion of banana residues be adopted as part of the solution to embracing renewable energy sources of energy and reduction of greenhouse gas emissions. Some of the recommendations include:

i) As part of the adoption of the anaerobic digestion technique, Banana plant residues are highly organic and also have high moisture content if not stored properly most of its gas content might be lost, and also bad smells may be emitted to the atmosphere and insects and scavengers may be attracted to the waste, so good storage is required. To deal with this, the best storage methods should be devised to reduce the moisture before digestion. Sun-drying or ensiling (forming silage) of the waste before the digestion has shown to be some of the appropriate ways for preparation of the waste for digestion and also for storage, these methods should be researched further to see how appropriate it is with regards to banana plant residues.

ii) To scale-up operation for a batch system from laboratory to full-scale the process needs to be optimized for a continuous operation, and the engineering challenges are encouraged to be studied further.

iii) The structure of the bacterial community that was present in the degradation of the banana plant residues should be evaluated to be able to identify these cellulose-degrading microorganisms to improve the methane yield from substrates with hemicellulose and lignin material.

iv) The greenhouse gas emissions from the use of digestate in the land need to be quantified in field-scale experiments. This will help to evaluate the greenhouse gas emission reduction using anaerobic digestion of banana plant residues from a life cycle assessment perspective.

v) A cost-benefit analysis of anaerobic digestion of banana plant residues in a Kenyan farmer's farm, through the use of life cycle assessment, should be evaluated to be able to see the overall picture of the anaerobic digestion technique.

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APPENDICES

APPENDIX A: ANALYSIS OF THE BIOGAS PRODUCED BY GAS CHROMATOGRAPHY

	Readings												CO2 + CH4 Corrected for total gas measured=100%=Pressure		CO2 / CH4 ratio (Sum=100%)	
	Air (N_2+O_2) [%]	CH_4 [%]	CO_2 [%]	H_2S [%]	Pressure [mbar]	Pressure (Calculated) [mbar]	Air (N_2+O_2) [%]	CH_4 [%]	CO_2 [%]	H_2S [%]	Sum [%]	Pressure (Calculated) [mbar]	CH_4 [%]	CO_2 [%]	CH_4 [%]	CO_2 [%]
Blank		10.9	7.7	0.00069		188	Wrong	10.9	7.7	0					58.59	41.41
	31.66	4.78	3.36			1008	79.15	11.95	8.39		99.49	995			58.74	41.26
		10.86	7.13		990	182	Wrong	10.86	7.13				0.12	0.08	60.39	39.61
	31.66	8.85	6.06	0			79.15	11.24	7.74	0						
Stem		35.29	16.97	0.00056		529	Wrong	35.29	16.97	0					67.52	32.48
	27.78	14.41	6.89			1243	69.46	36.03	17.23		122.72	1227			67.65	32.35
					1190	0							0.29	0.14		
	27.78	24.85	11.93	0			69.46	35.66	17.1	0						
Leaf		25.61	12.8	0.00111		389	Wrong	25.61	12.8	0					66.67	33.33
	36.12	6.54	3.68			1174	90.3	16.36	9.2	0	115.86	1159				
					1150	0							0.14	0.08	64	36
	36.12	16.08	8.24	0.00111			90.3	20.99	11	0						
Peduncle		33.4	15.22	0.00161		493	Wrong	33.4	15.22	0					68.69	31.31
	23.62	13.77	6.22			1105	59.05	34.43	15.55		109.03	1090			68.89	31.11
					1190	0							0.32	0.14		
	23.62	23.59	10.72	0			59.05	33.92	15.39	0						

APPENDIX B: RESULTS OF ANAEROBIC DIGESTION

		Inoculum blank				Substrate: Stem			Substrate: leaf			Substrate: peduncle		
		TS	56.4	[g/kg]		TS	50.0 [g/kg]		TS	230.0 [g/kg]		TS	79.0 [g/kg]	
		oDM	40.9	[g/kg]		oDM	46.7 [g/kg]		oDM	206.8 [g/kg]		oDM	67.7 [g/kg]	
		COD	28,000	[mg/L]		NH4-N		[mg/L]	NH4-N		[mg/L]	NH4-N		[mg/L]
		pH		[-]		COD	48 [g/kg]		COD	237 [g/kg]		COD	70 [g/kg]	
		Temperatu	37.0	[°C]		pH		[-]	pH		[-]	pH		[-]
						Temperatu	37.0 [°C]		Temperatu	37.0 [°C]		Temperatu	37.0 [°C]	
		Blank				Stem			Leaf			Peduncle		
Inoculum	**[mL]**	250.00	250.00	250.00		250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
Substrate	**[g]**	0.00	0.00	0.00		21.63	21.63	21.63	4.70	4.70	4.70	13.69	13.69	13.69
water	**[mL]**	83.00	83.00	83.00		39.00	37.00	37.00	36.00	36.00	38.00	27.00	27.00	29.00
Sum	**[mL]**	333.00	333.00	333.00		310.63	308.63	308.63	290.70	290.70	292.70	290.69	290.69	292.69
Flask volume	**[ml]**	1160.79	1158.48	1157.79		1141.65	1134.02	1142.02	1114.55	1115.96	1116.26	1115.22	1116.37	1117.34
Gas volume	**[mL]**	827.79	825.48	824.79		831.02	825.39	833.39	823.85	825.26	823.56	824.53	825.68	824.65
oDM Inoculum	**[g]**	4.33	4.33	4.33		4.33	4.33	4.33	4.33	4.33	4.33	4.33	4.33	4.33
COD Substrate		0.00	0.00	0.00		1.03	1.03	1.03	1.11	1.11	1.11	0.96	0.96	0.96
oDM Substrate	**[g]**					1.01	1.01	1.01	0.97	0.97	0.97	0.93	0.93	0.93
oDMsubstrate /oDM Inoculum						0.23	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.21
Gas Analytics		Pressure recorded												
Sample Number		9	10	11		0	1	2	3	4	5	6	7	8
Time	days	1	2	3	4	5	6	7	8	9	10	11	12	13
	0	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	0.07	0.07	0.03		0.04	0.16	0.14	0.10	-0.03	0.12	0.09	0.13	0.10
	2	0.10	0.09	0.03			0.28	0.22	0.14		0.20	0.14	0.19	0.13
	3	0.10	0.10	0.04			0.39	0.35	0.20		0.28	0.18	0.23	0.20
	4	0.12	0.12	0.04			0.51	0.45	0.25		0.36	0.23	0.29	0.25
	5	0.12	0.12	0.04		-0.01	0.56	0.55	0.26	-0.02	0.38	0.38	0.29	0.39
	6	0.11	0.12	0.05		0.00	0.61	0.60	0.28	-0.03	0.40	0.44	0.37	0.45
	7	0.12	0.11	0.05		-0.02	0.63	0.62	0.30	-0.03	0.40	0.46	0.41	0.48
	8	0.13	0.12	0.05		-0.01	0.63	0.64	0.32	-0.02	0.42	0.48	0.45	0.50
	9	0.13	0.12	0.05		-0.01	0.66	0.66	0.34	-0.02	0.45	0.50	0.48	0.53
	10	0.14	0.12	0.05		-0.02	0.68	0.67	0.36	-0.03	0.47	0.52	0.52	0.55
	11	0.14	0.13	0.06		-0.02	0.69	0.68	0.38	-0.02	0.49	0.54	0.55	0.57
	12	0.15	0.13	0.06		-0.02	0.70	0.69	0.40	-0.02	0.51	0.56	0.57	0.59
	13	0.15	0.14	0.06		-0.02	0.71	0.70	0.42	-0.02	0.53	0.58	0.59	0.60
	14	0.16	0.14	0.06		-0.03	0.73	0.71	0.44	-0.04	0.56	0.59	0.61	0.62
	15	0.17	0.15	0.06		0.02	0.73	0.71	0.46	-0.01	0.56	0.60	0.61	0.62
	16	0.17	0.16	0.07		0.00	0.74	0.72	0.47	-0.02	0.58	0.61	0.64	0.64
	17	0.18	0.17	0.07		-0.01	0.75	0.73	0.49	-0.02	0.60	0.61	0.65	0.65
	18	0.18	0.17	0.07		-0.01	0.75	0.72	0.50	-0.02	0.61	0.62	0.67	0.66
	19	0.19	0.17	0.07		-0.02	0.76	0.73	0.52	-0.02	0.63	0.62	0.68	0.67
	20	0.19	0.18	0.08		-0.01	0.76	0.74	0.53	-0.01	0.64	0.63	0.69	0.68
	21	0.19	0.18	0.08		0.00	0.76	0.74	0.54	0.00	0.66	0.63	0.70	0.69
	22	0.20	0.18	0.08		0.00	0.77	0.74	0.55	-0.01	0.67	0.64	0.71	0.70
	23	0.20	0.19	0.09		0.00	0.77	0.74	0.57	-0.02	0.68	0.64	0.72	0.70
	24	0.21	0.19	0.08		-0.01	0.77	0.75	0.57	-0.03	0.69	0.64	0.72	0.71
	25	0.21	0.19	0.08		0.00	0.78	0.75	0.58	-0.03	0.70	0.65	0.73	0.71
	26	0.21	0.19	0.08		-0.03	0.78	0.75	0.59	-0.03	0.71	0.65	0.73	0.71
	27	0.22	0.20	0.08		-0.02	0.78	0.75	0.60	-0.03	0.71	0.65	0.73	0.72
	28	0.22	0.20	0.08		-0.01	0.78	0.75	0.61	-0.02	0.71	0.65	0.74	0.72
	29	0.23	0.21	0.09		-0.04	0.78	0.75	0.62	-0.02	0.71	0.65	0.74	0.72
	30	0.23	0.21	0.09		-0.03	0.78	0.76	0.62	-0.02	0.74	0.65	0.74	0.73
	31	0.23	0.21	0.09		-0.03	0.79	0.75	0.63	-0.02	0.75	0.65	0.75	0.73
	32	0.23	0.21	0.09		-0.03	0.79	0.75	0.63	-0.02	0.76	0.65	0.75	0.73
	33	0.24	0.21	0.10		-0.03	0.79	0.75	0.64	-0.02	0.77	0.65	0.75	0.73
	34	0.24	0.21	0.10		-0.03	0.79	0.75	0.64	-0.02	0.77	0.65	0.75	0.74
	35	0.24	0.21	0.10		-0.04	0.79	0.75	0.65	-0.02	0.78	0.65	0.76	0.74
	36	0.24	0.21	0.10		-0.04	0.79	0.75	0.65	-0.02	0.79	0.65	0.76	0.74
	37	0.25	0.21	0.09		-0.04	0.79	0.75	0.65	-0.03	0.80	0.65	0.76	0.74
	38	0.25	0.21	0.09		-0.04	0.79	0.75	0.66	-0.03	0.81	0.65	0.76	0.74
	39	0.25	0.21	0.10		-0.04	0.79	0.74	0.66	-0.02	0.81	0.65	0.76	0.74
	40	0.25	0.20	0.10		-0.04	0.79	0.74	0.66	-0.02	0.81	0.64	0.76	0.74
	41	0.26	0.20	0.10		-0.04	0.79	0.74	0.67	-0.02	0.82	0.64	0.77	0.74
	42	0.26	0.20	0.10		-0.04	0.79	0.74	0.67	-0.02	0.82	0.64	0.77	0.74
	43	0.26	0.20	0.10		-0.03	0.79	0.74	0.67	-0.01	0.82	0.64	0.77	0.75
	44	0.26	0.20	0.10		-0.03	0.79	0.74	0.68	-0.01	0.82	0.64	0.77	0.75
	45	0.26	0.20	0.11		-0.03	0.78	0.74	0.69	-0.01	0.83	0.63	0.77	0.75
	46	0.26	0.19	0.11		-0.03	0.78	0.73	0.69	-0.01	0.83	0.63	0.77	0.75
	47	0.26	0.19	0.11		0.27	0.78	0.73	0.69	0.20	0.83	0.63	0.77	0.75
	48	0.27	0.19	0.11		0.27	0.78	0.73	0.70	0.20	0.84	0.63	0.77	0.75
	49	0.27	0.17	0.11		0.28	0.78	0.72	0.71	0.20	0.86	0.62	0.77	0.75
	50	0.27	0.16	0.11		0.28	0.78	0.72	0.71	0.21	0.86	0.62	0.78	0.75
	51	0.27	0.16	0.11		0.29	0.78	0.72	0.71	0.21	0.86	0.61	0.78	0.75

APPENDIX C: AVERAGE CALCULATED BIOGAS VALUES

DAY	BLANK (ml)	STEM (ml)	LEAF (ml)	PEDUNCLE (ml)
0	0	0	0	0
1	40.54	106.17	78.45	75.96
2	52.23	180.93	122.74	109.79
3	57.38	266.35	171.22	147.28
4	66.58	347.66	218.48	184
5	66.58	397.51	228.8	255.91
6	66.52	437.28	241.65	301.48
7	67.36	452.5	248.49	322.35
8	70.07	458.87	264.75	341.86
9	73.54	474.21	280.86	361.26
10	75.63	485.38	296.69	380.05
11	78.98	494.9	312.23	396.95
12	81.4	503.22	326.62	411.37
13	85.09	511.36	341.51	424.04
14	87.17	517.92	355.48	434.85
15	91.67	520.65	363	436.98
16	95.98	525.51	376.14	449.53
17	98.23	530.64	388.78	459.29
18	100.58	531.74	400.13	467.42
19	102.78	536.32	411.02	473.94
20	105.87	539.64	420.72	479.4
21	109.2	542.17	429.74	483.91
22	112.03	544.33	437.66	487.88
23	114.25	546.02	445.68	491.71
24	115.04	547.71	452.77	494.84
25	115.98	548.82	459.53	497.95
26	116.87	549.83	464.98	499.86
27	118.78	550.19	469.67	501.44
28	121.68	550.73	472.5	503.5
29	124.31	553.15	476.83	505.84
30	125.97	556.88	488.93	507.23
31	127.52	555.46	492.58	508.59
32	128.41	555.06	498.67	509.64
33	129.56	553.21	503.93	510.6
34	130.64	555.35	507.87	511.46
35	131.05	554.76	512.1	512.27
36	131.74	554.69	516.64	513.04
37	131.31	554.29	520.22	513.45
38	131.6	553.64	524.05	514.09
39	132.3	551.79	525.92	514.43
40	132.9	551.43	528.49	514.16
41	133.73	551.18	530.32	514.98
42	133.26	550.17	531.32	514.45
43	134	549.52	535.4	514.52
44	134.62	548.8	538.2	514.29
45	135.03	547.96	541.53	514.26
46	135.46	547.57	544.68	514.29
47	134.93	546.85	546.97	514.64
48	134.41	546.23	549.44	514.57
49	131.3	540.92	560.9	512.21
50	130.73	539.95	562.98	511.56
51	130.73	539.95	563.66	511.11

APPENDIX D: BIOGAS VALUES WITHOUT THE INOCULUM

DAY	BLANK (ml)	STEM (ml)	LEAF (ml)	PEDUNCLE (ml)
0	0	0	0	0
1	40.54	65.63	37.91	35.42
2	52.23	128.7	70.51	57.56
3	57.38	208.97	113.84	89.9
4	66.58	281.09	151.91	117.43
5	66.58	330.94	162.22	189.33
6	66.52	370.75	175.13	234.95
7	67.36	385.13	181.13	254.99
8	70.07	388.8	194.68	271.79
9	73.54	400.67	207.32	287.71
10	75.63	409.75	221.06	304.42
11	78.98	415.92	233.25	317.97
12	81.4	421.82	245.22	329.97
13	85.09	426.28	256.43	338.96
14	87.17	430.75	268.31	347.68
15	91.67	428.98	271.33	345.3
16	95.98	429.53	280.16	353.55
17	98.23	432.4	290.55	361.05
18	100.58	431.16	299.55	366.83
19	102.78	433.54	308.23	371.16
20	105.87	433.77	314.85	373.52
21	109.2	432.96	320.54	374.71
22	112.03	432.3	325.63	375.86
23	114.25	431.77	331.42	377.46
24	115.04	432.67	337.72	379.8
25	115.98	432.84	343.55	381.97
26	116.87	432.97	348.11	382.99
27	118.78	431.41	350.88	382.66
28	121.68	429.05	350.81	381.82
29	124.31	428.84	352.51	381.53
30	125.97	430.91	362.96	381.26
31	127.52	427.94	365.06	381.07
32	128.41	426.65	370.26	381.23
33	129.56	423.65	374.37	381.04
34	130.64	424.71	377.23	380.82
35	131.05	423.72	381.05	381.23
36	131.74	422.95	384.9	381.3
37	131.31	422.98	388.91	382.13
38	131.6	422.04	392.45	382.49
39	132.3	419.5	393.62	382.13
40	132.9	418.54	395.6	381.27
41	133.73	417.44	396.59	381.24
42	133.26	416.91	398.07	381.2
43	134	415.52	401.41	380.53
44	134.62	414.17	403.58	379.66
45	135.03	412.94	406.5	379.23
46	135.46	412.11	409.22	378.83
47	134.93	411.91	412.04	379.71
48	134.41	411.82	415.03	380.16
49	131.3	409.62	429.6	380.91
50	130.73	409.22	432.25	380.83
51	130.73	409.22	432.93	380.38

APPENDIX E: BIOGAS VALUES WITHOUT THE INOCULUM IN (mL Biogas/g oDM Substrate)

DAY	BLANK	STEMl)	LEAF	PEDUNCLE
0	0	0	0	0
1	9.36	64.93	38.99	38.24
2	12.06	127.33	72.52	62.15
3	13.25	206.75	117.1	97.06
4	15.38	278.1	156.26	126.79
5	15.38	327.41	166.86	204.42
6	15.36	366.81	180.14	253.68
7	15.56	381.03	186.31	275.31
8	16.18	384.66	200.25	293.46
9	16.98	396.41	213.25	310.64
10	17.47	405.4	227.38	328.68
11	18.24	411.49	239.92	343.32
12	18.8	417.33	252.24	356.27
13	19.65	421.74	263.77	365.97
14	20.13	426.17	275.98	375.39
15	21.17	424.41	279.09	372.82
16	22.17	424.96	288.17	381.73
17	22.69	427.8	298.86	389.83
18	23.23	426.57	308.12	396.07
19	23.74	428.93	317.05	400.74
20	24.45	429.15	323.85	403.29
21	25.22	428.36	329.71	404.58
22	25.87	427.7	334.95	405.82
23	26.39	427.17	340.91	407.54
24	26.57	428.06	347.38	410.07
25	26.79	428.24	353.38	412.41
26	26.99	428.36	358.07	413.52
27	27.43	426.82	360.92	413.16
28	28.1	424.48	360.85	412.25
29	28.71	424.27	362.6	411.94
30	29.09	426.33	373.35	411.65
31	29.45	423.38	375.5	411.44
32	29.66	422.11	380.85	411.62
33	29.92	419.14	385.08	411.41
34	30.17	420.19	388.03	411.18
35	30.26	419.21	391.95	411.61
36	30.43	418.45	395.91	411.69
37	30.33	418.48	400.04	412.59
38	30.39	417.55	403.68	412.98
39	30.55	415.03	404.88	412.59
40	30.69	414.08	406.92	411.66
41	30.89	413	407.93	411.63
42	30.78	412.48	409.46	411.58
43	30.95	411.1	412.89	410.85
44	31.09	409.77	415.12	409.92
45	31.18	408.54	418.13	409.46
46	31.28	407.72	420.93	409.02
47	31.16	407.53	423.83	409.98
48	31.04	407.44	426.91	410.47
49	30.32	405.26	441.89	411.26
50	30.19	404.87	444.61	411.19
51	30.19	404.87	445.31	410.7

APPENDIX F: BIOGAS VALUES WITHOUT THE INOCULUM IN (mL Biogas / g oDM Inoculum)

DAY	BLANK	STEM	LEAF	PEDUNCLE
0	0	0	0	0
1	9.36	15.16	8.75	8.18
2	12.06	29.72	16.28	13.29
3	13.25	48.26	26.29	20.76
4	15.38	64.92	35.08	27.12
5	15.38	76.43	37.46	43.73
6	15.36	85.62	40.44	54.26
7	15.56	88.94	41.83	58.89
8	16.18	89.79	44.96	62.77
9	16.98	92.53	47.88	66.45
10	17.47	94.63	51.05	70.3
11	18.24	96.05	53.87	73.43
12	18.8	97.42	56.63	76.21
13	19.65	98.45	59.22	78.28
14	20.13	99.48	61.96	80.3
15	21.17	99.07	62.66	79.75
16	22.17	99.2	64.7	81.65
17	22.69	99.86	67.1	83.38
18	23.23	99.57	69.18	84.72
19	23.74	100.12	71.18	85.72
20	24.45	100.18	72.71	86.26
21	25.22	99.99	74.03	86.54
22	25.87	99.84	75.2	86.8
23	26.39	99.72	76.54	87.17
24	26.57	99.92	78	87.71
25	26.79	99.96	79.34	88.21
26	26.99	99.99	80.39	88.45
27	27.43	99.63	81.04	88.37
28	28.1	99.09	81.02	88.18
29	28.71	99.04	81.41	88.11
30	29.09	99.52	83.83	88.05
31	29.45	98.83	84.31	88.01
32	29.66	98.53	85.51	88.04
33	29.92	97.84	86.46	88
34	30.17	98.08	87.12	87.95
35	30.26	97.86	88	88.04
36	30.43	97.68	88.89	88.06
37	30.33	97.69	89.82	88.25
38	30.39	97.47	90.64	88.33
39	30.55	96.88	90.91	88.25
40	30.69	96.66	91.36	88.05
41	30.89	96.41	91.59	88.05
42	30.78	96.28	91.93	88.04
43	30.95	95.96	92.7	87.88
44	31.09	95.65	93.2	87.68
45	31.18	95.37	93.88	87.58
46	31.28	95.17	94.51	87.49
47	31.16	95.13	95.16	87.69
48	31.04	95.11	95.85	87.8
49	30.32	94.6	99.21	87.97
50	30.19	94.51	99.83	87.95
51	30.19	94.51	99.98	87.85

APPENDIX G: BIOGAS VALUES WITHOUT THE INOCULUM IN (mL Biogas / g COD Substrate)

DAY	BLANK	STEM	LEAF	PEDUNCLE
0	0	0	0	0
1	9.36	63.88	34.05	36.79
2	12.06	125.26	63.32	59.8
3	13.25	203.4	102.25	93.4
4	15.38	273.59	136.43	122
5	15.38	322.1	145.69	196.7
6	15.36	360.86	157.29	244.1
7	15.56	374.85	162.67	264.91
8	16.18	378.42	174.84	282.37
9	16.98	389.97	186.2	298.91
10	17.47	398.82	198.54	316.27
11	18.24	404.81	209.48	330.35
12	18.8	410.56	220.24	342.81
13	19.65	414.9	230.31	352.15
14	20.13	419.25	240.97	361.21
15	21.17	417.53	243.69	358.74
16	22.17	418.06	251.62	367.3
17	22.69	420.86	260.95	375.1
18	23.23	419.65	269.03	381.11
19	23.74	421.97	276.83	385.6
20	24.45	422.19	282.77	388.06
21	25.22	421.41	287.89	389.3
22	25.87	420.76	292.46	390.48
23	26.39	420.24	297.66	392.14
24	26.57	421.12	303.32	394.58
25	26.79	421.29	308.55	396.83
26	26.99	421.41	312.64	397.9
27	27.43	419.89	315.14	397.55
28	28.1	417.6	315.08	396.67
29	28.71	417.39	316.6	396.37
30	29.09	419.41	325.99	396.1
31	29.45	416.51	327.87	395.9
32	29.66	415.26	332.54	396.07
33	29.92	412.34	336.23	395.87
34	30.17	413.37	338.8	395.64
35	30.26	412.41	342.23	396.06
36	30.43	411.66	345.69	396.13
37	30.33	411.69	349.29	397
38	30.39	410.77	352.47	397.37
39	30.55	408.3	353.52	397
40	30.69	407.36	355.3	396.1
41	30.89	406.3	356.18	396.08
42	30.78	405.78	357.51	396.03
43	30.95	404.43	360.51	395.33
44	31.09	403.12	362.46	394.44
45	31.18	401.91	365.09	393.99
46	31.28	401.11	367.53	393.57
47	31.16	400.92	370.06	394.49
48	31.04	400.83	372.75	394.96
49	30.32	398.69	385.83	395.73
50	30.19	398.3	388.21	395.65
51	30.19	398.3	388.82	395.18

APPENDIX H: METHANE VALUES

DAY	BLANK (ML)	STEM (ML)	LEAF (ML)	PEDUNCLE (ML)
0	0	0	0	0
1	4.87	19.03	5.31	11.33
2	6.27	37.32	9.87	18.42
3	6.89	60.6	15.94	28.77
4	7.99	81.52	21.27	37.58
5	7.99	95.97	22.71	60.59
6	7.98	107.52	24.52	75.19
7	8.08	111.69	25.36	81.6
8	8.41	112.75	27.25	86.97
9	8.83	116.19	29.02	92.07
10	9.08	118.83	30.95	97.41
11	9.48	120.62	32.65	101.75
12	9.77	122.33	34.33	105.59
13	10.21	123.62	35.9	108.47
14	10.46	124.92	37.56	111.26
15	11	124.4	37.99	110.5
16	11.52	124.56	39.22	113.13
17	11.79	125.4	40.68	115.54
18	12.07	125.04	41.94	117.39
19	12.33	125.73	43.15	118.77
20	12.7	125.79	44.08	119.53
21	13.1	125.56	44.88	119.91
22	13.44	125.37	45.59	120.27
23	13.71	125.21	46.4	120.79
24	13.81	125.47	47.28	121.53
25	13.92	125.52	48.1	122.23
26	14.02	125.56	48.74	122.56
27	14.25	125.11	49.12	122.45
28	14.6	124.42	49.11	122.18
29	14.92	124.36	49.35	122.09
30	15.12	124.96	50.81	122
31	15.3	124.1	51.11	121.94
32	15.41	123.73	51.84	121.99
33	15.55	122.86	52.41	121.93
34	15.68	123.17	52.81	121.86
35	15.73	122.88	53.35	121.99
36	15.81	122.66	53.89	122.02
37	15.76	122.66	54.45	122.28
38	15.79	122.39	54.94	122.4
39	15.88	121.65	55.11	122.28
40	15.95	121.38	55.38	122.01
41	16.05	121.06	55.52	122
42	15.99	120.9	55.73	121.98
43	16.08	120.5	56.2	121.77
44	16.15	120.11	56.5	121.49
45	16.2	119.75	56.91	121.35
46	16.26	119.51	57.29	121.22
47	16.19	119.45	57.69	121.51
48	16.13	119.43	58.1	121.65
49	15.76	118.79	60.14	121.89
50	15.69	118.67	60.51	121.87
51	15.69	118.67	60.61	121.72

APPENDIX I: METHANE VALUES IN (mL Biogas / g oDM Substrate)

DAY	BLANK	STEM	LEAF	PEDUNCLE
0	0	0	0	0
1	1.12	18.83	5.46	12.24
2	1.45	36.93	10.15	19.89
3	1.59	59.96	16.39	31.06
4	1.85	80.65	21.88	40.57
5	1.85	94.95	23.36	65.41
6	1.84	106.37	25.22	81.18
7	1.87	110.5	26.08	88.1
8	1.94	111.55	28.03	93.91
9	2.04	114.96	29.85	99.41
10	2.1	117.56	31.83	105.18
11	2.19	119.33	33.59	109.86
12	2.26	121.03	35.31	114.01
13	2.36	122.31	36.93	117.11
14	2.42	123.59	38.64	120.12
15	2.54	123.08	39.07	119.3
16	2.66	123.24	40.34	122.15
17	2.72	124.06	41.84	124.75
18	2.79	123.71	43.14	126.74
19	2.85	124.39	44.39	128.24
20	2.93	124.45	45.34	129.05
21	3.03	124.22	46.16	129.47
22	3.1	124.03	46.89	129.86
23	3.17	123.88	47.73	130.41
24	3.19	124.14	48.63	131.22
25	3.21	124.19	49.47	131.97
26	3.24	124.22	50.13	132.33
27	3.29	123.78	50.53	132.21
28	3.37	123.1	50.52	131.92
29	3.45	123.04	50.76	131.82
30	3.49	123.63	52.27	131.73
31	3.53	122.78	52.57	131.66
32	3.56	122.41	53.32	131.72
33	3.59	121.55	53.91	131.65
34	3.62	121.85	54.32	131.58
35	3.63	121.57	54.87	131.72
36	3.65	121.35	55.43	131.74
37	3.64	121.36	56.01	132.03
38	3.65	121.09	56.52	132.15
39	3.67	120.36	56.68	132.03
40	3.68	120.08	56.97	131.73
41	3.71	119.77	57.11	131.72
42	3.69	119.62	57.32	131.71
43	3.71	119.22	57.8	131.47
44	3.73	118.83	58.12	131.18
45	3.74	118.48	58.54	131.03
46	3.75	118.24	58.93	130.89
47	3.74	118.18	59.34	131.19
48	3.72	118.16	59.77	131.35
49	3.64	117.53	61.86	131.6
50	3.62	117.41	62.25	131.58
51	3.62	117.41	62.34	131.42

APPENDIX J: METHANE VALUES IN (mL Biogas / g COD Substrate)

DAY	BLANK	STEM	LEAF	PEDUNCLE
0	0	0	0	0
1	1.12	18.52	4.77	11.77
2	1.45	36.33	8.87	19.14
3	1.59	58.98	14.31	29.89
4	1.85	79.34	19.1	39.04
5	1.85	93.41	20.4	62.94
6	1.84	104.65	22.02	78.11
7	1.87	108.71	22.77	84.77
8	1.94	109.74	24.48	90.36
9	2.04	113.09	26.07	95.65
10	2.1	115.66	27.8	101.21
11	2.19	117.4	29.33	105.71
12	2.26	119.06	30.83	109.7
13	2.36	120.32	32.24	112.69
14	2.42	121.58	33.74	115.59
15	2.54	121.08	34.12	114.8
16	2.66	121.24	35.23	117.54
17	2.72	122.05	36.53	120.03
18	2.79	121.7	37.66	121.96
19	2.85	122.37	38.76	123.39
20	2.93	122.44	39.59	124.18
21	3.03	122.21	40.3	124.57
22	3.1	122.02	40.94	124.96
23	3.17	121.87	41.67	125.49
24	3.19	122.12	42.46	126.26
25	3.21	122.17	43.2	126.99
26	3.24	122.21	43.77	127.33
27	3.29	121.77	44.12	127.21
28	3.37	121.1	44.11	126.94
29	3.45	121.04	44.32	126.84
30	3.49	121.63	45.64	126.75
31	3.53	120.79	45.9	126.69
32	3.56	120.43	46.56	126.74
33	3.59	119.58	47.07	126.68
34	3.62	119.88	47.43	126.61
35	3.63	119.6	47.91	126.74
36	3.65	119.38	48.4	126.76
37	3.64	119.39	48.9	127.04
38	3.65	119.12	49.35	127.16
39	3.67	118.41	49.49	127.04
40	3.68	118.14	49.74	126.75
41	3.71	117.83	49.87	126.75
42	3.69	117.68	50.05	126.73
43	3.71	117.28	50.47	126.51
44	3.73	116.9	50.74	126.22
45	3.74	116.55	51.11	126.08
46	3.75	116.32	51.45	125.94
47	3.74	116.27	51.81	126.24
48	3.72	116.24	52.19	126.39
49	3.64	115.62	54.02	126.63
50	3.62	115.51	54.35	126.61
51	3.62	115.51	54.44	126.46

APPENDIX K: LEAVES GOMPERTZ MODELLING RESULTS

```
* Nonlinear Regression.
MODEL PROGRAM  P=50 R=0.8 L=5.
COMPUTE  PRED_=P * EXP( - EXP(((R * 2.7183)/P) * (L - days) + 1)).
NLR methane
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss15288\SPSSFNLR.TMP'
  /PRED_
  /SAVE PRED RESID DERIVATIVES
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		26-FEB-2021 15:39:25
Comments		
Input	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	52
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=50 R=0.8 L=5. COMPUTE PRED_=P * EXP(- EXP(((R * 2.7183)/P) * (L - days) + 1)). NLR methane /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss15288\SPSSFNLR.TMP' /PRED_ /SAVE PRED RESID DERIVATIVES /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.02
	Elapsed Time	00:00:00.01
Variables Created or Modified	PRED_	Predicted Values
	RESID	Residuals
	D.P	d(Pred)/d(P)
	D.R	d(Pred)/d(R)

Notes

Variables Created or Modified	D.L	d(Pred)/d(L)
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss15288\SPSSFNLR.TMP

[DataSet0]

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	38506.539	50.000	.800	5.000
1.1	2733.305	69.861	.703	-37.562
2.0	2733.305	69.861	.703	-37.562
2.1	59988.579	36.586	1.524	23.288
2.2	2145.423	96.549	.736	-31.219
3.0	2145.423	96.549	.736	-31.219
3.1	1655.135	87.075	.816	-28.364
4.0	1655.135	87.075	.816	-28.364
4.1	1372.785	72.009	.964	-20.546
5.0	1372.785	72.009	.964	-20.546
5.1	939.542	68.820	1.135	-15.486
6.0	939.542	68.820	1.135	-15.486
6.1	1038.944	57.524	1.483	-7.818
6.2	706.020	64.894	1.288	-12.473
7.0	706.020	64.894	1.288	-12.473
7.1	555.128	59.238	1.597	-7.151
8.0	555.128	59.238	1.597	-7.151
8.1	334.787	57.801	1.917	-4.779
9.0	334.787	57.801	1.917	-4.779
9.1	295.431	57.863	2.020	-4.530
10.0	295.431	57.863	2.020	-4.530
10.1	294.954	57.754	2.043	-4.413
11.0	294.954	57.754	2.043	-4.413
11.1	294.940	57.727	2.047	-4.396
12.0	294.940	57.727	2.047	-4.396
12.1	294.940	57.721	2.048	-4.392
13.0	294.940	57.721	2.048	-4.392
13.1	294.940	57.720	2.048	-4.392
14.0	294.940	57.720	2.048	-4.392
14.1	294.940	57.720	2.048	-4.392

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 30 model evaluations and 14 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.000E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	57.720	.819	56.074	59.365
R	2.048	.103	1.840	2.256
L	-4.392	.737	-5.873	-2.911

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.642	-.499
R	-.642	1.000	.912
L	-.499	.912	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	108451.060	3	36150.353
Residual	294.940	49	6.019
Uncorrected Total	108746.000	52	
Corrected Total	11390.231	51	

Dependent variable: methane[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .974.

APPENDIX L: LEAVES LOGISTIC MODELLING RESULTS

```
* NonLinear Regression.
MODEL PROGRAM  P=120 R=0.5 L=5.
COMPUTE  PRED_=P/ (1 + EXP(((4 * R * (L -T)) / P)   + 2)).
NLR Y
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss8672\SPSSFNLR.TMP'
  /PRED_
  /SAVE PRED
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		03-FEB-2021 18:19:57
Comments		
Input	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	52
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=120 R=0.5 L=5. COMPUTE PRED_=P/ (1 + EXP(((4 * R * (L -T)) / P) + 2)). NLR Y /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss8672\SPSSFNLR.TMP' /PRED_ /SAVE PRED /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.05
	Elapsed Time	00:00:00.05
Variables Created or Modified	PRED_	Predicted Values
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss8672\SPSSFNLR.TMP

```
[DataSet0]
```

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	35844.510	120.000	.500	5.000
1.1	2822223905.993	-7323.782	-23.684	-4251.855
1.2	15788832.679	-577.935	-1.213	-448.430
1.3	35444.295	167.861	1.246	-28.608
2.0	35444.295	167.861	1.246	-28.608
2.1	14107.176	155.602	1.150	-24.090
3.0	14107.176	155.602	1.150	-24.090
3.1	1364.811	70.334	.920	-22.776
4.0	1364.811	70.334	.920	-22.776
4.1	7973.357	41.514	1.361	-5.526
4.2	1241.687	64.145	.973	-21.633
5.0	1241.687	64.145	.973	-21.633
5.1	1011.855	64.000	1.069	-17.910
6.0	1011.855	64.000	1.069	-17.910
6.1	780.206	58.888	1.279	-11.909
7.0	780.206	58.888	1.279	-11.909
7.1	534.489	57.888	1.515	-8.303
8.0	534.489	57.888	1.515	-8.303
8.1	449.917	56.687	1.764	-5.624
9.0	449.917	56.687	1.764	-5.624
9.1	425.518	56.718	1.818	-5.638
10.0	425.518	56.718	1.818	-5.638
10.1	424.937	56.596	1.843	-5.445
11.0	424.937	56.596	1.843	-5.445
11.1	424.899	56.562	1.847	-5.419
12.0	424.899	56.562	1.847	-5.419
12.1	424.896	56.553	1.849	-5.409
13.0	424.896	56.553	1.849	-5.409
13.1	424.896	56.551	1.849	-5.407
14.0	424.896	56.551	1.849	-5.407
14.1	424.896	56.550	1.849	-5.407

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
15.0	424.896	56.550	1.849	-5.407
15.1	424.896	56.550	1.849	-5.407

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 33 model evaluations and 15 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.000E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	56.550	.820	54.902	58.198
R	1.849	.111	1.626	2.073
L	-5.407	1.050	-7.516	-3.297

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.498	-.387
R	-.498	1.000	.930
L	-.387	.930	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	108254.851	3	36084.950
Residual	424.896	49	8.671
Uncorrected Total	108679.747	52	
Corrected Total	11361.390	51	

Dependent variable: Y[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .963.

APPENDIX M: STEM GOMPERTZ MODELLING RESULTS

```
* NonLinear Regression.

MODEL PROGRAM  P=100 R=0.2 L=5.
COMPUTE  PRED_=P * EXP(-EXP(((R * 2.7183) / P) * (L-T) + 1)).
NLR Y
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP'
  /PRED_
  /SAVE PRED
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		02-FEB-2021 11:14:42
Comments		
Input	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	52
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=100 R=0.2 L=5. COMPUTE PRED_=P * EXP(-EXP(((R * 2.7183) / P) * (L-T) + 1)). NLR Y /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP' /PRED PRED_ /SAVE PRED /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.06
	Elapsed Time	00:00:00.09
Variables Created or Modified	PRED_1	Predicted Values
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP

```
[DataSet0]
```

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	602073.655	100.000	.200	5.000
1.1	1964203513.128	-6032.476	-7.218	-5056.721
1.2	2833292.419	646.206	.601	-555.379
1.3	240946.376	217.131	.575	-58.681
2.0	240946.376	217.131	.575	-58.681
2.1	51744.817	311.831	.784	-90.823
3.0	51744.817	311.831	.784	-90.823
3.1	705452.202	-259.368	.700	-138.292
3.2	38111.256	317.453	.814	-95.338
4.0	38111.256	317.453	.814	-95.338
4.1	26241.615	296.506	.871	-104.118
5.0	26241.615	296.506	.871	-104.118
5.1	704997.808	-15.868	.889	-103.382
5.2	26070.439	263.999	.875	-104.413
6.0	26070.439	263.999	.875	-104.413
6.1	25871.505	198.419	.881	-104.344
7.0	25871.505	198.419	.881	-104.344
7.1	25665.497	189.247	.912	-102.463
8.0	25665.497	189.247	.912	-102.463
8.1	25457.761	183.554	.965	-96.114
9.0	25457.761	183.554	.965	-96.114
9.1	25152.408	167.473	1.078	-84.823
10.0	25152.408	167.473	1.078	-84.823
10.1	24628.413	163.236	1.200	-75.439
11.0	24628.413	163.236	1.200	-75.439
11.1	24352.043	146.607	1.451	-59.858
12.0	24352.043	146.607	1.451	-59.858
12.1	22885.260	144.664	1.718	-49.858
13.0	22885.260	144.664	1.718	-49.858
13.1	22253.083	132.949	2.251	-34.189
14.0	22253.083	132.949	2.251	-34.189

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
14.1	19206.691	132.104	2.798	-27.151
15.0	19206.691	132.104	2.798	-27.151
15.1	17260.707	126.455	3.892	-14.991
16.0	17260.707	126.455	3.892	-14.991
16.1	12778.933	125.500	4.957	-12.004
17.0	12778.933	125.500	4.957	-12.004
17.1	10041.133	124.112	7.086	-4.727
18.0	10041.133	124.112	7.086	-4.727
18.1	5256.178	123.039	9.218	-3.960
19.0	5256.178	123.039	9.218	-3.960
19.1	3543.105	122.922	13.481	-.381
20.0	3543.105	122.922	13.481	-.381
20.1	697.048	122.497	17.745	-.319
21.0	697.048	122.497	17.745	-.319
21.1	348.554	122.710	22.425	.471
22.0	348.554	122.710	22.425	.471
22.1	273.570	122.825	23.151	.364
23.0	273.570	122.825	23.151	.364
23.1	273.285	122.818	23.335	.385
24.0	273.285	122.818	23.335	.385
24.1	273.285	122.818	23.332	.384
25.0	273.285	122.818	23.332	.384
25.1	273.285	122.818	23.332	.384

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 54 model evaluations and 25 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.000E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	122.818	.365	122.083	123.552
R	23.332	.819	21.687	24.977
L	.384	.101	.181	.587

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.179	-.112
R	-.179	1.000	.847
L	-.112	.847	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	704724.523	3	234908.174
Residual	273.285	49	5.577
Uncorrected Total	704997.808	52	
Corrected Total	35645.075	51	

Dependent variable: Y[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .992.

APPENDIX N: STEM LOGISTIC MODELLING RESULTS

```
* NonLinear Regression.
MODEL PROGRAM  P=120 R=1 L=5.
COMPUTE  PRED_=P/ (1 + EXP(((4 * R * (L - T)) / P)   + 2)).
NLR Y
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss20516\SPSSFNLR.TMP'
  /PRED PRED_
  /SAVE PRED RESID
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		03-FEB-2021 08:06:42
Comments		
Input	Data	C:\Users\damke\OneDrive\Desktop\PHD RESULTS AND DOCUMENTS\Untitled1.sav
	Active Dataset	DataSet2
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	52
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=120 R=1 L=5. COMPUTE PRED_=P/ (1 + EXP(((4 * R * (L - T)) / P) + 2)). NLR Y /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss20516\SPSSFNLR.TMP' /PRED PRED_ /SAVE PRED RESID /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.06
	Elapsed Time	00:00:00.08
Variables Created or Modified	PRED_	Predicted Values

Notes

Variables Created or Modified	RESID	Residuals
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss20516\SPSSFNLR.TMP

[DataSet2]

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	419887.298	120.000	1.000	5.000
1.1	80038137.269	-1126.912	-8.532	-522.904
1.2	30619.134	464.557	1.754	-33.946
2.0	30619.134	464.557	1.754	-33.946
2.1	135483.272	245.607	.573	-85.818
2.2	28036.518	521.914	1.605	-32.979
3.0	28036.518	521.914	1.605	-32.979
3.1	27151.269	560.596	1.290	-40.710
4.0	27151.269	560.596	1.290	-40.710
4.1	27142.900	448.874	1.085	-66.653
5.0	27142.900	448.874	1.085	-66.653
5.1	26915.710	390.781	1.025	-79.772
6.0	26915.710	390.781	1.025	-79.772
6.1	26602.974	271.324	.868	-104.593
7.0	26602.974	271.324	.868	-104.593
7.1	731163.547	-183.836	.645	-146.334
7.2	25936.564	196.766	.871	-105.637
8.0	25936.564	196.766	.871	-105.637
8.1	199052.643	57.523	.919	-102.482
8.2	25726.473	181.697	.873	-105.627
9.0	25726.473	181.697	.873	-105.627
9.1	25642.058	154.690	.884	-105.652
10.0	25642.058	154.690	.884	-105.652
10.1	25451.707	161.182	.899	-104.024
11.0	25451.707	161.182	.899	-104.024
11.1	25309.024	156.197	.930	-100.656
12.0	25309.024	156.197	.930	-100.656
12.1	25011.060	153.522	.989	-93.655
13.0	25011.060	153.522	.989	-93.655
13.1	24487.891	144.793	1.119	-80.806
14.0	24487.891	144.793	1.119	-80.806

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
14.1	24058.967	135.456	1.414	-58.739
15.0	24058.967	135.456	1.414	-58.739
15.1	21870.295	131.281	1.765	-46.189
16.0	21870.295	131.281	1.765	-46.189
16.1	20940.359	126.602	2.437	-27.524
17.0	20940.359	126.602	2.437	-27.524
17.1	16237.413	123.848	3.155	-21.889
18.0	16237.413	123.848	3.155	-21.889
18.1	15312.436	124.020	4.590	-9.443
19.0	15312.436	124.020	4.590	-9.443
19.1	10038.545	122.968	5.241	-11.313
20.0	10038.545	122.968	5.241	-11.313
20.1	7784.409	124.819	6.542	-6.198
21.0	7784.409	124.819	6.542	-6.198
21.1	4718.150	122.268	9.149	-3.017
22.0	4718.150	122.268	9.149	-3.017
22.1	2355.193	122.808	11.757	-1.889
23.0	2355.193	122.808	11.757	-1.889
23.1	1734.772	122.407	16.974	.387
24.0	1734.772	122.407	16.974	.387
24.1	530.518	122.549	19.663	.107
25.0	530.518	122.549	19.663	.107
25.1	459.480	122.520	22.242	.509
26.0	459.480	122.520	22.242	.509
26.1	449.138	122.503	22.564	.479
27.0	449.138	122.503	22.564	.479
27.1	448.917	122.489	22.722	.496
28.0	448.917	122.489	22.722	.496
28.1	448.911	122.486	22.735	.496
29.0	448.911	122.486	22.735	.496
29.1	448.911	122.486	22.738	.496

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
30.0	448.911	122.486	22.738	.496
30.1	448.911	122.486	22.739	.496

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 64 model evaluations and 30 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.000E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	122.486	.460	121.561	123.410
R	22.739	1.101	20.526	24.951
L	.496	.150	.195	.797

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.116	-.069
R	-.116	1.000	.881
L	-.069	.881	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	704548.896	3	234849.632
Residual	448.911	49	9.161
Uncorrected Total	704997.808	52	
Corrected Total	35645.075	51	

Dependent variable: Y[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .987.

APPENDIX O: PEDUNCLE GOMPERTZ MODELLING RESULTS

```
* NonLinear Regression.
MODEL PROGRAM  P=60 R=0.5 L=5.
COMPUTE  PRED_=P * EXP(-EXP(((R  * 2.7183)/P) * (L-T) + 1)).
NLR y
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP'
  /PRED PRED_
  /SAVE PRED RESID DERIVATIVES
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		02-FEB-2021 18:20:44
Comments		
Input	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	53
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=60 R=0.5 L=5. COMPUTE PRED_=P * EXP(-EXP(((R * 2.7183)/P) * (L-T) + 1)). NLR y /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP' /PRED PRED_ /SAVE PRED RESID DERIVATIVES /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.03
	Elapsed Time	00:00:00.02
Variables Created or Modified	PRED_	Predicted Values
	RESID	Residuals
	D.P	d(Pred)/d(P)
	D.R	d(Pred)/d(R)

Notes

Variables Created or Modified	D.L	d(Pred)/d(L)
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss6692\SPSSFNLR.TMP

[DataSet1]

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	498844.754	60.000	.500	5.000
1.1	41912134.999	-807.531	-2.915	-476.824
1.2	141909.166	300.552	1.004	-30.540
2.0	141909.166	300.552	1.004	-30.540
2.1	33983.777	128.784	1.184	-80.558
3.0	33983.777	128.784	1.184	-80.558
3.1	319957.735	172.191	1.892	12.526
3.2	30113.427	144.776	1.124	-74.728
4.0	30113.427	144.776	1.124	-74.728
4.1	27160.927	180.005	1.167	-63.044
5.0	27160.927	180.005	1.167	-63.044
5.1	24099.489	189.065	1.371	-52.031
6.0	24099.489	189.065	1.371	-52.031
6.1	24037.577	150.019	1.752	-34.955
7.0	24037.577	150.019	1.752	-34.955
7.1	19664.811	152.037	2.022	-31.737
8.0	19664.811	152.037	2.022	-31.737
8.1	17585.817	137.553	2.532	-21.629
9.0	17585.817	137.553	2.532	-21.629
9.1	14225.865	134.494	3.054	-16.979
10.0	14225.865	134.494	3.054	-16.979
10.1	11115.681	126.256	4.097	-8.884
11.0	11115.681	126.256	4.097	-8.884
11.1	6635.294	124.970	5.157	-6.462
12.0	6635.294	124.970	5.157	-6.462
12.1	4191.650	121.847	7.274	-1.369
13.0	4191.650	121.847	7.274	-1.369
13.1	977.141	121.301	9.398	-.699
14.0	977.141	121.301	9.398	-.699
14.1	409.232	121.272	11.668	.548
15.0	409.232	121.272	11.668	.548

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
15.1	294.500	121.407	12.136	.431
16.0	294.500	121.407	12.136	.431
16.1	292.992	121.359	12.298	.494
17.0	292.992	121.359	12.298	.494
17.1	292.967	121.350	12.312	.495
18.0	292.967	121.350	12.312	.495
18.1	292.967	121.349	12.314	.496
19.0	292.967	121.349	12.314	.496
19.1	292.967	121.349	12.314	.496
20.0	292.967	121.349	12.314	.496
20.1	292.967	121.349	12.314	.496

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	121.349	.423	120.499	122.198
R	12.314	.342	11.627	13.001
L	.496	.148	.198	.794

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.271	-.173
R	-.271	1.000	.852
L	-.173	.852	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	629858.033	3	209952.678
Residual	292.967	49	5.979
Uncorrected Total	630151.000	52	
Corrected Total	51166.981	51	

Dependent variable: y[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .994.

APPENDIX P: PEDUNCLE LOGISTIC MODELLING RESULTS

```
* NonLinear Regression.
MODEL PROGRAM  P=100 R=0.8 L=7.
COMPUTE  PRED_=P/(1 + EXP(((4 * R * (L  - time)) /P) + 2)).
NLR methane
  /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss8056\SPSSFNLR.TMP'
  /PRED PRED_
  /SAVE PRED RESID
  /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
```

Nonlinear Regression Analysis

Notes

Output Created		26-FEB-2021 16:18:50
Comments		
Input	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	52
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used. Predicted values are calculated for cases with missing values on the dependent variable.
Syntax		MODEL PROGRAM P=100 R=0.8 L=7. COMPUTE PRED_=P/(1 + EXP(((4 * R * (L - time)) /P) + 2)). NLR methane /OUTFILE='C:\Users\damke\AppData\Local\Temp\spss8056\SPSSFNLR.TMP' /PRED PRED_ /SAVE PRED RESID /CRITERIA SSCONVERGENCE 1E-8 PCON 1E-8.
Resources	Processor Time	00:00:00.02
	Elapsed Time	00:00:00.03
Variables Created or Modified	PRED_	Predicted Values
	RESID	Residuals
Files Saved	Parameter Estimates File	C:\Users\damke\AppData\Local\Temp\spss8056\SPSSFNLR.TMP

```
[DataSet0]
```

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
1.0	411987.784	100.000	.800	7.000
1.1	401796023.316	-2674.024	-16.351	-1152.426
1.2	57183.158	285.843	.516	-135.418
2.0	57183.158	285.843	.516	-135.418
2.1	1311456.638	-891.784	.499	-339.116
2.2	34588.045	245.405	.622	-149.025
3.0	34588.045	245.405	.622	-149.025
3.1	630253.927	-62.866	.685	-131.394
3.2	33882.906	216.622	.623	-146.003
4.0	33882.906	216.622	.623	-146.003
4.1	33782.492	170.104	.642	-140.009
5.0	33782.492	170.104	.642	-140.009
5.1	33333.088	202.646	.643	-138.125
6.0	33333.088	202.646	.643	-138.125
6.1	33035.799	192.227	.659	-135.378
7.0	33035.799	192.227	.659	-135.378
7.1	32720.830	227.209	.685	-128.640
8.0	32720.830	227.209	.685	-128.640
8.1	32696.397	166.602	.702	-126.000
9.0	32696.397	166.602	.702	-126.000
9.1	32177.298	199.736	.703	-124.173
10.0	32177.298	199.736	.703	-124.173
10.1	31876.126	189.968	.720	-121.815
11.0	31876.126	189.968	.720	-121.815
11.1	31590.581	225.567	.747	-115.718
12.0	31590.581	225.567	.747	-115.718
12.1	31714.170	161.805	.764	-113.706
12.2	31215.204	196.303	.756	-114.995
13.0	31215.204	196.303	.756	-114.995
13.1	30965.448	194.899	.770	-112.343
14.0	30965.448	194.899	.770	-112.343

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
14.1	30485.647	193.914	.798	-107.394
15.0	30485.647	193.914	.798	-107.394
15.1	29641.678	181.517	.852	-98.654
16.0	29641.678	181.517	.852	-98.654
16.1	28644.050	220.437	.962	-82.042
17.0	28644.050	220.437	.962	-82.042
17.1	630151.000	-10.279	1.005	-81.908
17.2	28037.281	202.182	.969	-83.019
18.0	28037.281	202.182	.969	-83.019
18.1	28124.178	160.280	.983	-82.738
18.2	27815.367	183.290	.976	-83.121
19.0	27815.367	183.290	.976	-83.121
19.1	27673.798	183.233	.987	-82.149
20.0	27673.798	183.233	.987	-82.149
20.1	27407.554	180.099	1.008	-80.023
21.0	27407.554	180.099	1.008	-80.023
21.1	26908.477	179.577	1.048	-75.941
22.0	26908.477	179.577	1.048	-75.941
22.1	26253.524	157.097	1.128	-69.158
23.0	26253.524	157.097	1.128	-69.158
23.1	25380.331	180.873	1.207	-61.354
24.0	25380.331	180.873	1.207	-61.354
24.1	39164.597	108.099	1.280	-59.882
24.2	25124.622	172.640	1.213	-62.033
25.0	25124.622	172.640	1.213	-62.033
25.1	24970.693	160.091	1.229	-61.975
26.0	24970.693	160.091	1.229	-61.975
26.1	24783.604	169.011	1.244	-60.494
27.0	24783.604	169.011	1.244	-60.494
27.1	24511.873	155.800	1.280	-58.990
28.0	24511.873	155.800	1.280	-58.990

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
28.1	24176.408	165.797	1.308	-56.412
29.0	24176.408	165.797	1.308	-56.412
29.1	23774.564	147.865	1.374	-53.872

30.0	23774.564	147.865	1.374	-53.872
30.1	23064.837	159.395	1.435	-49.536
31.0	23064.837	159.395	1.435	-49.536
31.1	22429.330	138.172	1.568	-45.192
32.0	22429.330	138.172	1.568	-45.192
32.1	20959.309	148.964	1.698	-39.084
33.0	20959.309	148.964	1.698	-39.084
33.1	19681.023	129.960	1.969	-32.694
34.0	19681.023	129.960	1.969	-32.694
34.1	17108.714	137.119	2.242	-26.252
35.0	17108.714	137.119	2.242	-26.252
35.1	14601.017	125.384	2.761	-19.209
36.0	14601.017	125.384	2.761	-19.209
36.1	11260.929	127.540	3.314	-14.263
37.0	11260.929	127.540	3.314	-14.263
37.1	8297.441	122.350	4.422	-7.392
38.0	8297.441	122.350	4.422	-7.392
38.1	4650.096	122.244	5.532	-5.282
39.0	4650.096	122.244	5.532	-5.282
39.1	3346.518	121.009	7.751	-.645
40.1	1054.018	120.798	9.662	-.267
41.0	1054.018	120.798	9.662	-.267
41.1	801.704	120.838	11.115	.438
42.0	801.704	120.838	11.115	.438
42.1	761.209	120.739	11.517	.467
43.0	761.209	120.739	11.517	.467
43.1	758.575	120.667	11.704	.535

Iteration Number[a]	Residual Sum of Squares	Parameter		
		P	R	L
44.0	758.575	120.667	11.704	.535
44.1	758.375	120.643	11.746	.545
45.0	758.375	120.643	11.746	.545
45.1	758.361	120.637	11.758	.549
46.0	758.361	120.637	11.758	.549
46.1	758.360	120.635	11.762	.550
47.0	758.360	120.635	11.762	.550
47.1	758.360	120.635	11.762	.550
48.0	758.360	120.635	11.762	.550
48.1	758.360	120.634	11.763	.550

Derivatives are calculated numerically.[b]

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 103 model evaluations and 48 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.000E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
P	120.634	.654	119.320	121.949
R	11.763	.565	10.627	12.898
L	.550	.282	-.018	1.118

Correlations of Parameter Estimates

	P	R	L
P	1.000	-.180	-.113
R	-.180	1.000	.888
L	-.113	.888	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	629392.640	3	209797.547
Residual	758.360	49	15.477
Uncorrected Total	630151.000	52	
Corrected Total	51166.981	51	

Dependent variable: methane[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .985.