EVALUATION AND OPTIMIZATION OF BIOGAS PRODUCTION RATE FOR SELECTED ANAEROBIC DIGESTION FACTORS USING ANIMAL MANURES

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented in this university or any other for the award of a degree

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DEDICATION

This thesis is dedicated to my parents Mr. Josia Matwek and Mrs. Rose Matwek, my husband Jared Kipng'etich and our son Jedreck Kipkoech.

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ABSTRACT

Kenya depends mainly on biomass to meet its cooking energy demand. This has caused forests depletion at an alarming rate, leading to low water levels in hydro station dams causing power shortages. There is a need for alternative sources of energy such as biogas. The broad objective of this research was to evaluate and optimize the biogas production rate of various mix ratios, total solids and organic loading rates of animal manures. Cattle, pig and sheep manures were mixed at ten mix ratios of 1:1:1, 3:1:1, 1:3:1, 1:1:2, 2:1:1, 1:2:1, 1:1:2, 1:3:3, 3:3:1 and 3:1:3. Total solids (TS), carbon to nitrogen ratio (C/N), pH and volatile solids (VS) were determined using standard procedures. Determined TS for the pure cattle, pig and sheep manures were 19.18%, 23.50% and 30.35%, respectively and for the ten mixtures, the content varied from 22.28% to 26.75%. Mixing enabled C/N to fall within the recommended range which is between 20:1 and 30:1 except that of mix ratio1:3:1 which was18.76%. Their pH also varied from 7.133 to 7.567 which was within the tolerable range for methane formation which is from 5.5 to 8.5 and corresponding VS varied from 85.94% to 82.59%. Results were then subjected to principal component analysis to select 1:1:3, 3:1:3 and 1:1:2 which were ranked top for anaerobic digestion. Also, 6%, 8%, 10% and 12% TS and 1 - 4kgVS/day organic loading rates were examined using a 0.15m^3 fixed dome laboratory digester under 35±1℃ temperature. Taguchi approach was used to find the optimum combination of the three parameters in terms of maximum biogas yield. Mixture 1:1:2 gave a yield rate of 1.7 m^3/m^{3}day followed by 3:1:3 and 1:1:3 giving 1.3 m^3/m^{3}day and 0.782 m^3/m^{3}day, respectively. Pure sheep, pig and cattle manures gave 0.56 m^3/m^{3}day, 0.41 m^3/m^{3}day and 0.31 m^3/m^{3}day, respectively. Mean gas yields for 6%, 8%, 10% and 12% TS were 0.78 m^3/m^{3}day, 0.64 m^3/m^{3}day, 0.51 m^3/m^{3}day and 0.30 m^3/m^{3}day, respectively. Biogas production rate for 1kgVS/ m^{3}day, 2kgVS/ m^{3}day, 3kgVS/ m^{3}day and 4kgVS/m^{3}day OLR were 0.6 m^3/m^{3}day, 0.7 m^3/m^{3}day, 0.8 m^3/m^{3}day and 0.4 m^3/m^{3}day, respectively. Maximum biogas yield was attained at the combination 1:1:2, 8% and 3kgVS/m^{3}day. It was observed that mixing the three manures resulted in a corresponding variation of biophysical characteristics. The mixtures (1:1:3, 3:1:3 and 1:1:2) of cattle to pig to sheep manures gave more biogas than pure manures. There was a 21.4% increase in biogas yield as TS increased from 6 to 8% followed by a 61.5% decrease from 8% to 12%. Increasing loading rate from 1 to 3 kgVS/m^{3}day resulted in 29% increase in biogas yield followed by a 50% decrease as OLR was increased from 3 to 4 kgVS/m^{3}day. A mix ratio of 1:1:2, TS of 8% and 2 and 3 kgVS/m^3 day organic loading rates are recommended.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic digestion
C: N	Carbon to nitrogen ratio
COD	Chemical oxygen demand
HRT	Hydraulic retention time
OLR	Organic loading rate
pH	Negative logarithm of the hydrogen-ion (H^+) concentration
RT	Solids retention time
TS	Total solids
VS	Volatile solids
PM	Pig manure
CD	Cow dung
SM	Sheep manure
CC	Cow manure: Chicken manure
CS	Cow manure: Sheep manure
S/I	Substrate to inoculum ratio
SLSI	Sri Lanka Standards Institute
WAS	Waste activated sludge
OFMSW	Organic fraction of municipal solid waste
GS	Grass silage
KW	Kitchen waste
S/N	Signal to Noise ratio
FR	Feeding rate
EnDev	Energising Development
KIPPRA	Kenya Institute for Public Policy Research and Analysis
OFMSW	Organic fraction of municipal solid waste
CH_4	Methane
CO_2	Carbon (iv) oxide
H_2O	Water
H_2S	Hydrogen sulfide
NH_3	Ammonia
N	Nitrogen
C	Carbon
CH_3COOH	Acetic acid

CH_3CH_2COOH	Propionic acid
$CH_3CH_2CH_2COOH$	Butyric acid
CH_4	Methane
M^3	Cubic Meter
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
Kg	Kilogram
L	Litre
NH_3	Ammonia
^{o} C	Degree Celcius

CHAPTER ONE
INTRODUCTION

1.1 Background to the study

Energy systems in most developed and developing countries are based on fossil fuels. Dependence on fossil fuel is disadvantaged by environmental impacts, scarcity of supply and instability of prices and markets (Martins et al., 2019). According to Kuo (2019) oil supplies will end by 2052, gas supplies will last till 2060 and consequently 2090 for the coal. This foreseen problem has encouraged the exploration of alternative sources of energy to meet increasing demand. According to AfDB (2014), the annual consumption growth rate of various fuel types in Africa varies, the total projected growth rate of primary energy consumption for all types of fuel is 8.9%; Petroleum products with 6.5%, gas 8.6%, coal 2.7%, nuclear 18.5% and 5.8% for hydro.

Kenya depends mainly on biomass for its energy demand, which provides 68% of energy requirement and is foreseen to remain the main source of energy in the future (Mugo & Gathui, 2010). Kenya's forests have been depleted at an alarming rate of about 5,000 hectares per year in recent years. This is estimated to cause an annual reduction in water availability of about 62 million cubic meters (Ministry of Environment & Forestry, 2018). This increased rate of forest depletion has caused a rise in vulnerability due to drought resulting in low water levels in hydro station dams causing power shortages. Bearing in mind that rural households have to continue meeting their energy demand requirements, consideration has been to alternative sources of energy such as biogas which are clean, renewable and accessible.

Biogas technology is a sustainable and valid alternative to fossil fuels. It reduces greenhouse gas (GHG) emissions and can enhance energy security. It allows treatment of agricultural products, zoo technical byproducts and municipal wastes with a lesser effect on air quality when compared to combustion-based approaches for these biomasses. The gas can also be upgraded to bio-methane, appropriately used as a vehicle fuel or injected into national natural gas grids (Paolini et al., 2018). Biogas is an end product of the anaerobic digestion of organic matter. Some studies have been done aiming to increase biogas production. An example of such studies is co-digestion which is the combination of two or more different organic waste to produce a uniform mixture to be digested. It has the potential to contribute to a reduction in landfill disposal and also to the renewable energy budget (Viotti et al., 2004). Studies of co-digestion of banana and plantain peels, spent grains and rice husk, pig waste and cassava peels, sewage and brewery sludge have been done. The results show an improvement in methane yield as compared to that obtained from single substrates (Patil et al., 2011). Total solid (TS) and organic loading rate (OLR) are among the factors that influence biogas production. TS is a measurement of dry matter in sludge and is determined by drying of the sample at 103-105℃ in succession until no further change in weight is observed while organic Loading rate is the amount of organic matter fed to the digester at a regular interval (Meegoda et al., 2018).

A feedstock is any substance that can be converted into methane by bacteria. Examples include an anaerobic organic fraction of municipal solid waste, sewage sludge, grass clippings/garden waste, food remains and manure (cattle, pig, poultry). Others are energy crops, harvest remains and waste from food/beverage processing, dairy, starch industry, sugar industry, pharmaceutical industry, cosmetic industry, biochemical industry, pulp and paper, slaughterhouse/rendering plant (Steffen et al,.1998). Cow dung is a favorable substrate for co-digestion because it has nutrients such as metals, vitamins and other compounds necessary for microbial growth. It neutralizes pH and also has high water content which helps to dilute the concentrated organic wastes (Gashaw & Teshita, 2014).

1.2 Statement of the problem

Agriculture dominates Kenya's economy as the highest contributor to gross domestic product. About half of its agricultural yield is non-marketed subsistence production. There is potential for using biogas technology on small-scale farms to manage on-farm organic wastes (livestock dung/litter) and producing a clean renewable source of energy for cooking and lighting. Also, the bio-slurry from the biodigester is a very effective natural fertilizer significantly improving farm productivity (EnDev, 2018).

Anaerobic digestion of single substrates has some disadvantages associated with substrate properties. For example; Sewage sludge is characterized by low organic loads, animal manures have low organic loads and high nitrogen concentrations that may inhibit methanogens, the organic fraction of municipal solid waste has improper materials as well as a relatively high concentration of heavy metals, crops and agro-industrial wastes are seasonal substrates which might lack nitrogen and slaughterhouse wastes are associated with the high concentration of nitrogen and long chain fatty acids which inhibits methanogenic activity. Hence, the implementation of anaerobic co-digestion is required. Also, further considerations such as the selection of co-substrates and their mixing ratio should be taken (Rabii et al., 2019).

Despite the aforementioned benefits of anaerobic digestion, its potential is still under-exploited due to there being no well-established information available for the characteristics of various mix ratios, effects of various factors that affect the performance of bio-digesters such as various total solids, mix ratios, and organic loading rate among others and also the optimal values for the same parameters that result in maximum biogas production rate.

1.3 Objectives

1.3.1 Broad Objective

The broad objective of the study was to evaluate and optimize the biogas production rate of various mix ratios, total solids and organic loading rate of cattle, pig and sheep manures.

1.3.2 Specific objectives

Specific objectives were;

i. To characterize mix ratios of cattle, pig and sheep manures

ii. To determine biogas production rate of various mix ratios, total solids and organic loading rate of cattle manure, pig manure and sheep manure on biogas production

iii. To optimize biogas production rate with respect to mix ratios, total solids and organic loading rates using Taguchi design method.

1.4 Research Questions

i. How does the mixing of cattle manure, pig manure and sheep manure at varying ratios affect their characteristics?

ii. How do different mix ratios, total solids and organic loading rates of cattle, sheep and pig manures influence biogas production rate?

iii. What mix ratio, total solid and organic loading rate results in optimal biogas production rate?

1.5 Justification of the study

Unlike fossil fuel, firewood and charcoal, biogas is environmentally friendly and is a valuable resource for improving the socio-economic status of millions of people. It can be generated cheaply from locally available materials. Also, the skill required to build a bio-digester is simple and can create employment for the large population of energetic unemployed but trainable youths. Biogas digesters also produce slurry as one of the by-products which can be utilized to improve soil fertility.

Characterization of different mix ratios provided the information of their corresponding total solid, pH, carbon to nitrogen ratio and volatile solid values. Anaerobic digestion by varying the various factors including mix ratios, total solids and organic loading rates availed the information of their effects on biogas production rate. Evaluating the optimal mix ratio, total solids and organic loading rate for cattle manure, pig and sheep manures by use of Taguchi design method produced useful information; the right loading of the digester ensures micro-organisms are provided with the right nutrients for development and as a result prevents acidification, optimal mix ratio of manures ensures high biogas yield to meet daily energy requirement and optimal percentage of total solids for the same ensures the right amount of water to be added to the feedstock preventing clogging and consequently increases the level of microbial activity.

However, these ensure efficient operation of the biogas plant to lengthen its life and to ensure high gas yield to meet the energy demand, ensure access to clean, affordable, reliable and sustainable energy for all people living in rural communities and also to guarantee the health and wellbeing for people and hence realization of the sustainable development goals and hence vision 2030 (Rahman et al., 2019).

1.6 Scope and Limitations

The research uses cattle, pig and sheep manures for anaerobic digestion. The feedstocks were collected from the Egerton University Tatton Farm. Cattle manure, pig manure and sheep manure were mixed at the selected mix ratios of 1:1:1, 3:1:1, 1:3:1, 1:1:3, 1:1:2, 2:1:1, 1:2:1, 1:3:3, 3:3:1 and 3:1:3 respectively. Laboratory analysis of the mix ratios was limited to total solid, carbon to nitrogen ratio, pH and volatile solids. Principle component analysis was used to rank the mix ratios and optimization was done with the help of the Taguchi design method. For biogas production test temperature of 35ºC was maintained. The study was limited to biogas production rate, biogas quality and volatile solids degradation rate were not considered.

VARIABLES

Mix ratio (MR)

Total solids (TS)

Organic loading rate (OLR)

EXPERIMENTAL SET UP

- Lab bioreactor
- Semi-continuous
- Substrates:
  - Cow manure
  - Pig manure
  - Sheep manure

Held constant:

- Temperature (35±1℃)
- Substrate to inoculum ratio (5:1)
- Mixing frequency (4rpm everyday)
- Retention time (20 days).

OUTPUT

Biogas production rate(m^3/m^3day)

Figure 1. 1: Scope and limitations Flow chart

1.7 Definition of Terms

Biogas A combustible gas resulting from the decomposition of biological waste under anaerobic conditions.

Co- digestion Anaerobic digestion of two or more biodegradable feedstocks in an anaerobic digestion system.

Feedstock Organic material used in anaerobic digestion for generating biogas i.e. livestock manures, sewage sludge, waste feed, industrial waste, corn silage, food processing waste and slaughterhouse waste.

Mix ratios Abundance of one component of a mixture relative to that of all other components.

Total solids Residue remaining when the feedstock is dried at 105℃.

Volatile solids Solid in water or other liquids lost on drying solids at 550℃

Organic loading rate Quantity of organic material added per unit volume of the bio-digester reactor in a day and can be expressed as volatile solids or biological or chemical oxygen demand.

Anaerobic digestion Process of decomposition of organic matter by a wide range of micro-organisms in a complete absence of oxygen.

Fossil fuel Fuels in either solid, liquid or gaseous forms formed in the ground after millions of years through chemical and physical changes in plant and animal residues under high temperatures. Examples are crude oil, natural gas and coal.

pH	Expression of the intensity of acidic or alkaline strength of water. Range from 0-14, whereby 7 is neutral, 0 is the most acidic and 14 is the most alkaline.

CHAPTER TWO
LITERATURE REVIEW

2.1 Energy Situation in Kenya

Electricity accounts for only 9% of the total energy use in the country, petroleum products for 22% and biomass for 69%. The small share of electricity is due to mainly low and uneven connectivity in the country. Residential cooking, heating and lighting are powered almost entirely by biomass (Ngeno et al., 2018). More than 80% mainly low-income residents in urban areas rely on charcoal as their primary source of energy. High demand for wood fuel has unfavorably affected the environment by reducing tree cover, pollution and soil erosion. Also, social and economic impacts have been felt in terms of gender-based energy hardship that unpleasantly affect women and girls and also rise in the cost of energy which affects poor households (Mbali, 2018).

Also, almost 80% of poor household lighting is from paraffin which is carboniferous fuel. Its continuous usage increases carbon dioxide levels in the atmosphere, a greenhouse gas that causes global warming. Consumption of electricity has been increasingly growing leading to shortages due to over-reliance on hydro-power generation tied with inadequate power capacity. Kenya experienced an acute energy crisis this Era which has caused energy rationing. Several fossil-fueled power stations were mounted as well as contracting emergency suppliers to overcome this short-term devastation. Fossil fuels are costly and these were directly passed on to consumers accounting for about 40% of fuels' cost price. It results in rapid inflation and high living costs (SNV, 2014).

Kenya's Government tries to improve the livelihoods of people at the same time conserving the environment (Ndung'u, 2011). Overdependence on conventional energy sources is unmanageable and this poses an ultimate challenge to the energy sector. Hence, additional energy sources have to be pursued. Such alternative and renewable energy sources have received sufficient attention (Amigun & Von Blottnitz, 2007). Also, consciousness and worry about environmental impacts of fossil fuels with an abrupt rise in prices are associated with the slow migration to renewable energy sources (Akinbami, 2001).

Karekezi (2002) reported the development of renewable energy sources as a viable solution to energy problems in developing countries including Kenya. Energies to implement renewable energy sources option to complement the traditional sources and mitigate the current energy crisis have been progressively growing. Therefore, there is a pressing concern to study biogas biotechnology as an alternative renewable energy source.

2.2 Biogas Technology

2.2.1 Biogas Technology in Kenya

Biogas production is one of the oldest energy technologies. Van Helmont was the first person to note that organic material produces flammable gas and later John Dalton and Humphrey confirmed the gas to be methane (Abbasi et al., 2012). Mr. Tim Hutchinson introduced biogas in Kenya in 1947 and built the first biogas plant in 1957. Sludge was applied to the coffee trees and yield was greatly increased. In 1958 commercial purposes biogas plant was constructed whereby effluent was sold as the main product and gas as a useful by-product (Ndereba, 2012).

According to MoE (2004), the demand and design frameworks rose among large-scale farmers specifically in the 1970s during the global energy crisis. In 1984, the Special Energy Programme (SEP) under the auspices of the Ministry of Energy (MoE) conducted a biogas survey. The aim was to provide benchmark data that showed that of the 160 biogas plants installed in the country only 25% were in operation. MoE in partnership with the German Technical Cooperation (GTZ) embarked on a training and promotion program on understanding the importance of biogas bio-technology. Since then, the SEP and GTZ have been instrumental in the training and promotion of biogas human-resource in Kenya. Yet, associated challenges have slowed down the pace of this program predominantly high installation costs, inadequate technical expertise and inappropriate farming systems.

Almost 7,000 biogas digesters have been constructed under Kenya National Domestic Biogas Program (KENDBIP) with a target of 11,000 by the year 2020. KENDBIP was developed by the Kenya National Federation of Agricultural Producers (KENFAP), one of the organizations that promote biogas development in Kenya (Momanyi, 2015).

Biogas is an end product gas of anaerobic digestion of organic matter. It is renewable energy and can replace fossil fuel for heating, cooking, as vehicles' fuel and as a result, reduces the greenhouse gas emissions thus slowing down climate change.

2.2.2 Anaerobic Digestion Process

Biogas production takes place in four stages; hydrolysis, acidogenesis, acetogenesis and methanogenesis as described in Figure 2.1.

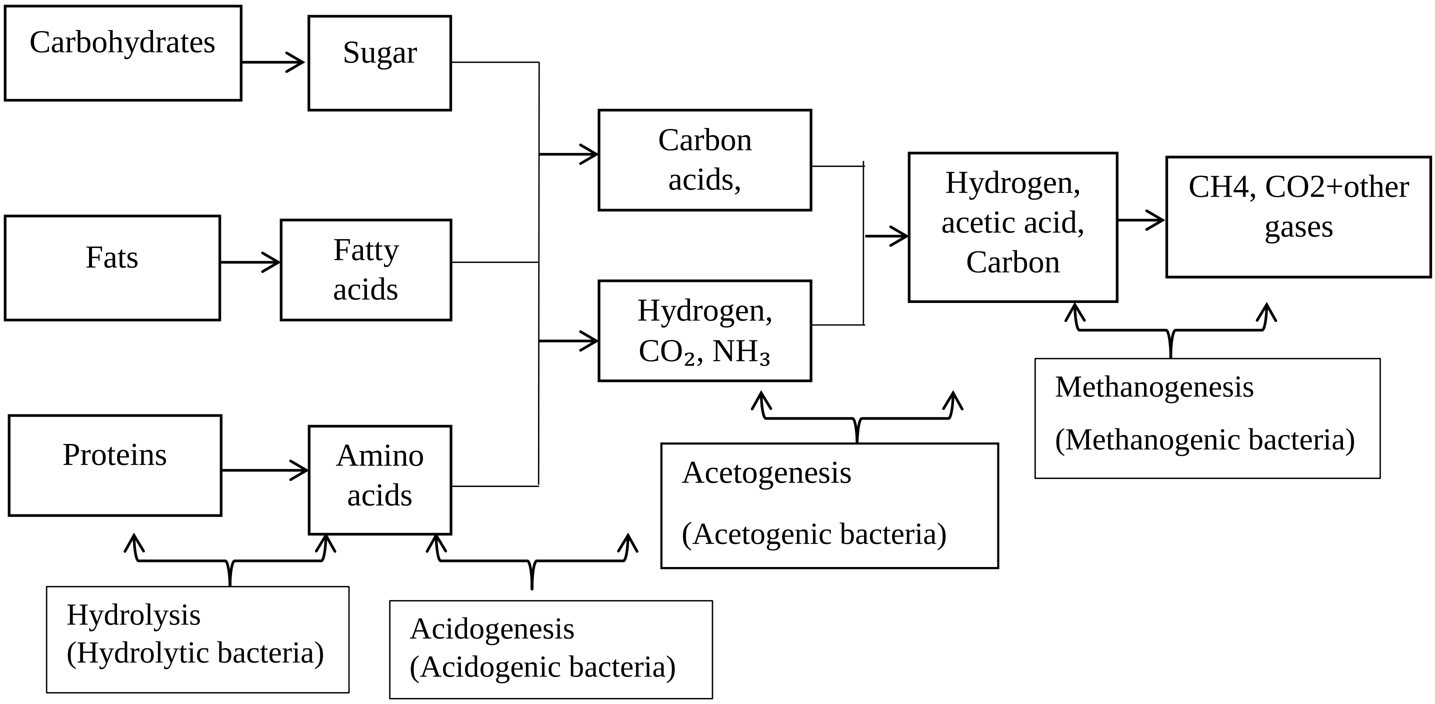

Figure 2.1: Anaerobic pathways in anaerobic degradation (Adapted from Salminen et al., 2002)

i. Hydrolysis

The process involves the depolymerization of insoluble complex organic hydrocarbons into soluble monomers. The principle substrate compounds (i.e., carbohydrates, lipids, and proteins) are broken down into corresponding low molecular weight monosaccharides, long-chain fatty acids, and amino acids that are favourable for bacterial degradation. It is a complex multistep process mediated by extracellular enzymes. The enzymes required for hydrolysis can either be attached to microbial cells or secreted to the solution (Angelidaki et al., 2011).

ii. Acidogenesis

In the acidogenesis stage, acidogenic bacteria such as Lactobacillus, Streptococcus, and Clostridium (Nayono, 2010) transform hydrolysis products (amino acids and sugars) into volatile fatty acids (acetic acid, butyric acid, and propionic acid), organic acids (succinic acid and lactic acid), ammonia (NH_3), hydrogen gas (H_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and low alcohols (EInstruments, 2019).

iii. Acetogenesis

The VFAs, especially acetic acids and butyric acids, into acetate, H_2 and CO_2. Among the VFAs, 65–95% of methane is directly produced from acetic acid, while propionic acid remains mainly unconverted because its degradation is thermodynamically less favorable (based on the relationship between hydrogen partial pressure and VFA degradation), in comparison to butyric acid (Felchner-Zwirello, 2014).

iv. Methanogenesis

The Methanogenesis process is the final stage of anaerobic digestion. Methane is generated by three groups of methanogens namely, acetotrophic, hydrogenotrophic and methylotrophic (Gerardi, 2003). The majority of the methane is produced by the acetotrophic methanogens which transform the acetate (resulting from acetogenesis) into CH_4 and CO_2 (Andre et al., 2016). The principle reaction in this process can be interpreted by Equation (2.1) shown below.

$$CH_3COOH \rightarrow CH_4+CO_2 \quad (2.1)$$

The hydrogenotrophic group converts hydrogen and carbon dioxide into methane through the reactions stated in Equations (2.2) and (2.3) (Andre et al., 2016). From this route, around 30% of methane may be produced.

$$CO_2+4H_2 \rightarrow CH_4+2H_2O \quad (2.2)$$

$$4CO + 2H_2O \rightarrow CH_4+3CO_2 \quad (2.3)$$

Besides the above two groups, some methane can also be produced by the methylotrophic methanogens (Gerardi, 2003). Through this pathway, the methyl or trimethylamine component of a given feedstock is transformed into methane following the chemical reactions given by Equations (2.4) and (2.5).

$$3CH_3OH + 3H_2 \rightarrow 3CH_4+3H_2O \quad (2.4)$$

$$4(CH_3)_3N + 6H_2O \rightarrow 9CH_4+3CO_2+4NH_3 \quad (2.5)$$

Biogas comprises mainly of methane, carbon dioxide and traces of other gases as described in Table 2.1.

Table 2. 1: Biogas composition

Gas component	Concentration range		
Methane (CH_4)	45-70%	55-60%	50-75%
Carbon dioxide (CO_2)	25-55%	35-40%	25-50%
Water vapour	0-10%	2-7%	0-3%
Nitrogen (N_2)	0.01-5%	0-2%	0-10%
Oxygen (O_2)	0.01-2%	0-2%	0-2%
Hydrogen (H_2)	0-1%	0-1%	0-1%
Ammonia (NH_3)	0.01-2.5mg/m^3n	-	-
Hydrogen sulfide (H_2S)	10-30000 mg/m^3n	20-20000ppm (2%)	0-2%
Source	Rakican (2007)	Suyog (2011)	Madigan et al. (2003)

2.3 Classification of Bio-digesters

2.3.1 Bio-digester Defined

Bio-digesters are plants that are used to store waste for anaerobic digestion to occur. Figure 2.2 describes the environmental and social benefits of bio-digesters.

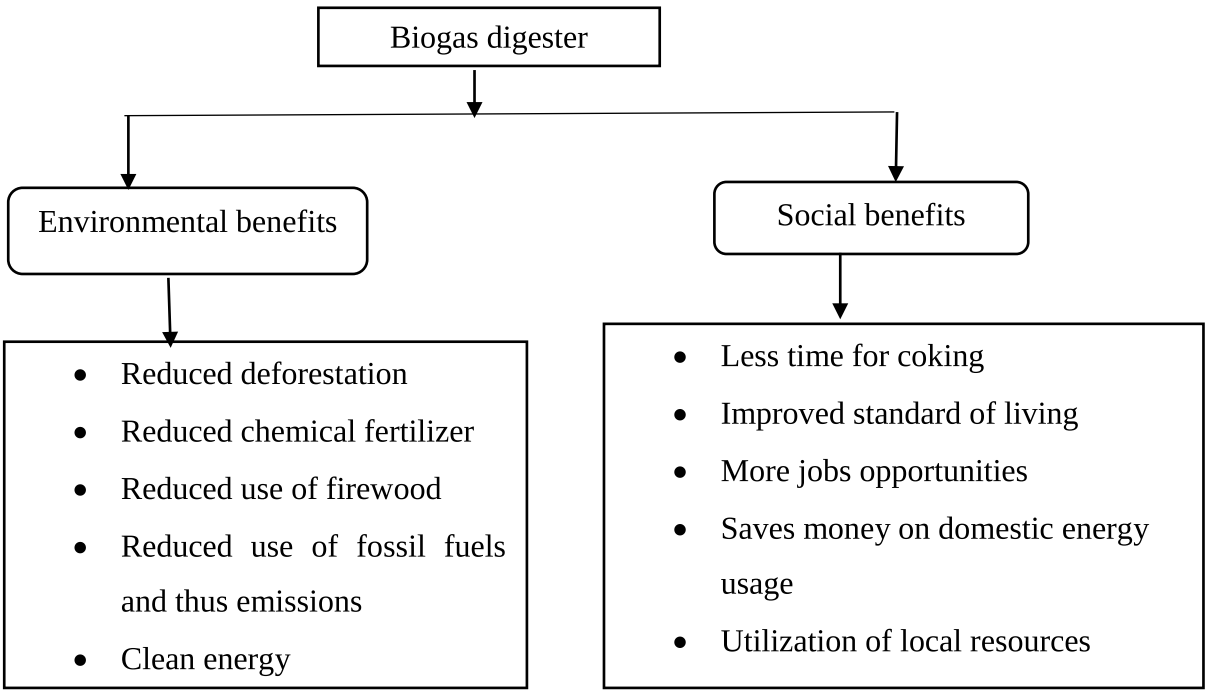

Figure 2.2: Environmental and social benefits in using biogas (Adapted from Rajendran et al., 2012)

2.3.2 Classification by Feeding Regime

According to Haryanto et al. (2018) anaerobic digesters can be classified in mainly three types based on the feeding strategy; batch, semi-continuous and continuous mode as described in the proceeding subsections.

a) Batch Feeding Digesters

Substrates are fed into the digester and sealed for digestion and after the biogas production cease it is emptied and re-filled with fresh raw materials. An advantage of this type of digester is it requires little daily attention. Its disadvantage is that greater energy is required when loading and emptying and also, the gas and sludge production is irregular.

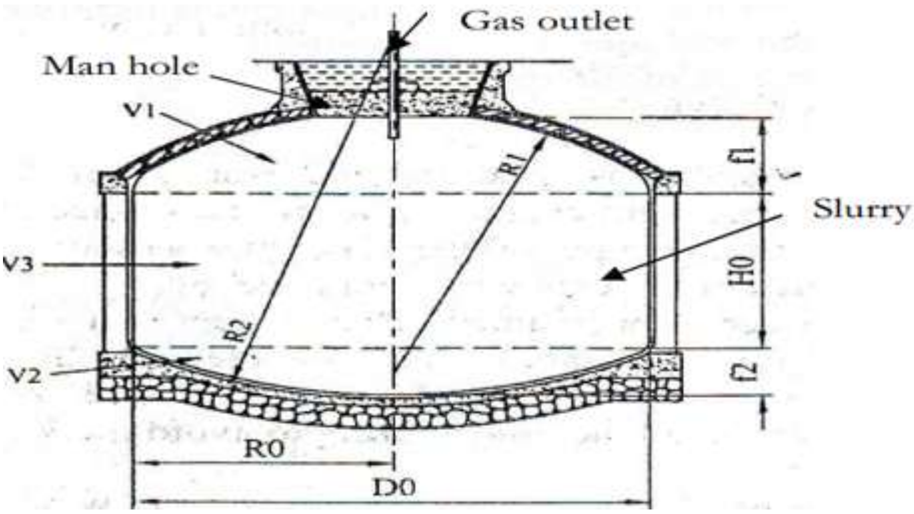

Figure 2.3: Batch type digester (SLSI, 2006)

b) Semi-continuous Load Digesters

In this process a quarter to half of the substrate material is fed inside the digester as the start-up of the digestion. During the digestion process fresh material is fed and some digested material is taken out intermittently. Biogas production for this type of digester is steady but the startup process and discharging are labour exhaustive.

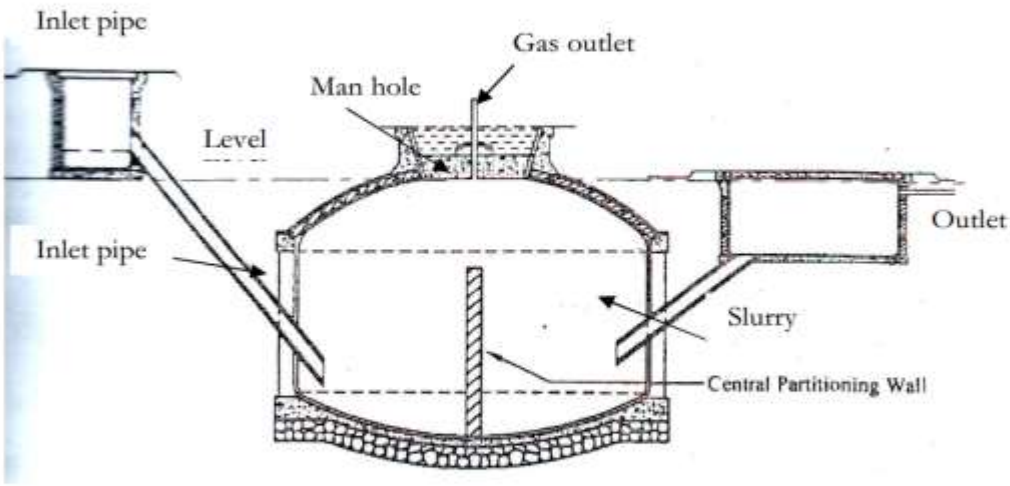

Figure 2.4: Semi-continuous digester (SLSI, 2006)

c) Continuous Fed Digesters

Substrates of the same amount are regularly fed. The rate of biogas and sludge production is regular and reliable. They are efficient when easily digestible wastes such as livestock manures are regularly fed (Sasse et al., 1991).

2.3.3 Classification by Digester Design

a) Fixed Dome Digester

Consists of an underground brick masonry section with a dome-shaped on top which stores the gas produced. The fermentation and gas chamber are combined in one unit as shown in Figure 2.5.

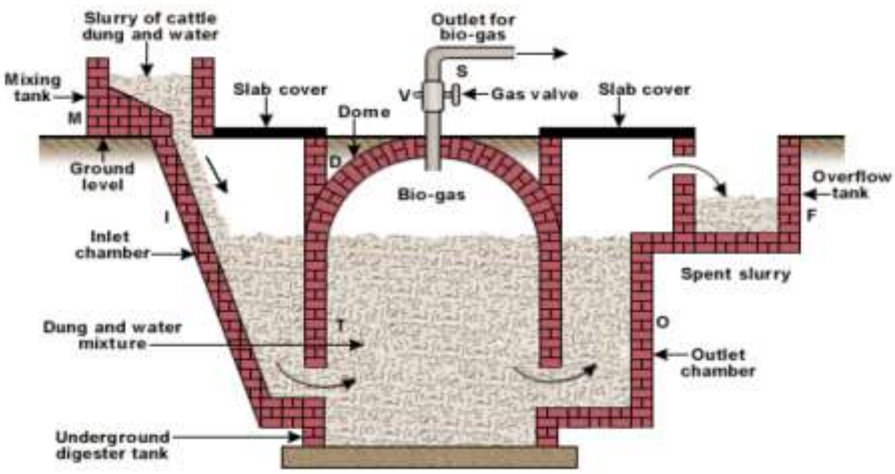

Figure 2.5: Fixed dome digester (Cheng & Liu, 2002)

b) Floating Drum

The floating drum digester is made of concrete divided into two parts; one part has the inlet where feedstock is fed to the tank and has a cylindrical dome that floats on the substrates as in Figure 2. 6.

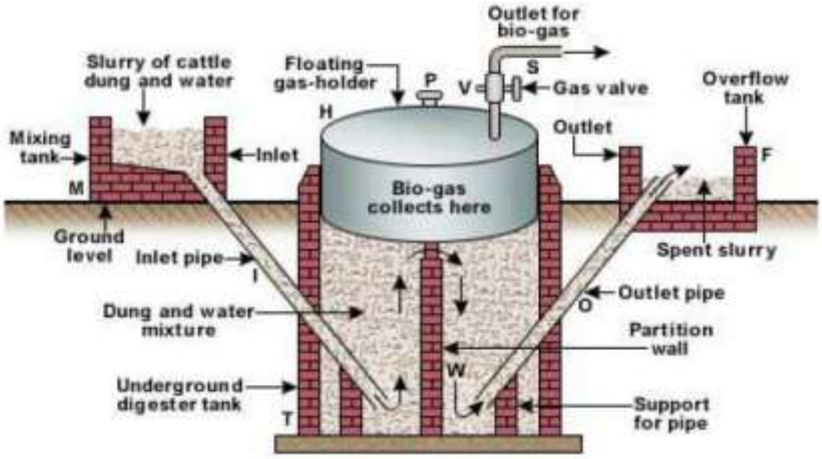

Figure 2.6: Floating drum digester (Cheng & Liu, 2002)

2.3.4 Classification Based on Biological Change of Feedstock

a) One-phase Digestion

Hydrolysis, acidogenesis and methanogenesis processes occur in a single digester. Biogas yield per reactor volume per unit mass of feedstock for this type of digestion is less compared to two-phase digestion reason being methane production phase is affected by the acid produced (Perera, 2011).

b) Two-phase Digestion

Hydrolysis and acidogenesis stages take place in a separate digester while the methanogenesis phase occurs in another type of digester which is suitable for the methanogenesis process. This results in more biogas production rate per digester volume per unit mass of the feedstock (Perera, 2011).

2.4 Factors Affecting Biogas Production

Anaerobic digestion is affected by pH, temperature, retention time, particle size, total solid content, volatile solid content, inoculums, dry matter content and organic loading rate (Monnet, 2003).

a) Total Solid

Total solid (TS) is the dry matter of a substrate and is expressed as the percentage of the total weight in grams per kilogram (Budiyon & Syaichurrozi, 2014). TS content is divided into three ranges; Low solids content (< 10% TS), medium solids content (15-20%) and high solids content which is from 22-40% (Monnet, 2003). The concentration of the waste influenced the pH, temperature and effectiveness of the microorganisms in the decomposition process (Igoni et al., 2008). Biogas production drops with a continuous increase of TS values, the reason being the water volume drops which consequently decreases the level of microbial activity (Yavini et al., 2014).

Orhorhoro et al. (2017) studied the effects of TS on biogas yield by AD of water hyacinth, waste water (i.e., from ice fish cold room, septic tanks, and abattoir), pig dung, cow dung, corn cobs, potato peels, pineapple peels, rice left over, yam peels, cassava peels, orange peels, sweet potato peels, garri left over, plantain peels, beans waste, banana peels, vegetables and concluded that digesters should be run optimally at around 10.16% TS. Budiyono et al. (2014) and Balsam (2006) reported that optimal biogas production from cow manure occurs at a TS of 8%. Paramaguru et al. (2017) studied the effects of 5 %, 15%, 10% and 20 % TS on biogas yield and found that anaerobic digestion of food waste should be done at 10% as it gave the highest biogas yield.

b) Temperature

Anaerobic digestion takes place at three different temperature ranges. Most on-farm biogas plants operate at psychrophilic (16ºC), lower Mesophilic (16-30ºC) and normal Mesophilic (17-35ºC) or Thermophilic temperature (35-55ºC) range (Comino et al.,2009). Biogas production rate increase with an increase in temperature but methane percentage decreases. 32-35℃ temperature ranges are most efficient for continuous and stable methane production. Carbon dioxide and other gases are higher percentages when the anaerobic digestion is outside this range. If the temperature is lower than 20℃, biogas production falls sharply and almost stops at about 10℃. Methanogenic bacteria are very sensitive to temperature changes and therefore relative stability of temperature must be ensured (Sorathia et al., 2012).

Thermophilic temperature is more efficient in terms of retention time, loading rate and biogas production but is disadvantaged by higher heat requirement and higher sensitivity to both operating and environmental variables. This makes the process more problematic than mesophilic temperature (Monnet, 2003).

Sichilalu et al. (2017) evaluated the optimal temperature for boosting biogas production through optimal constraining of the mesophilic temperature between log phase for the best growth of methanogenic bacteria. The findings of the biogas yield against temperature were as shown in Figure 2.7.

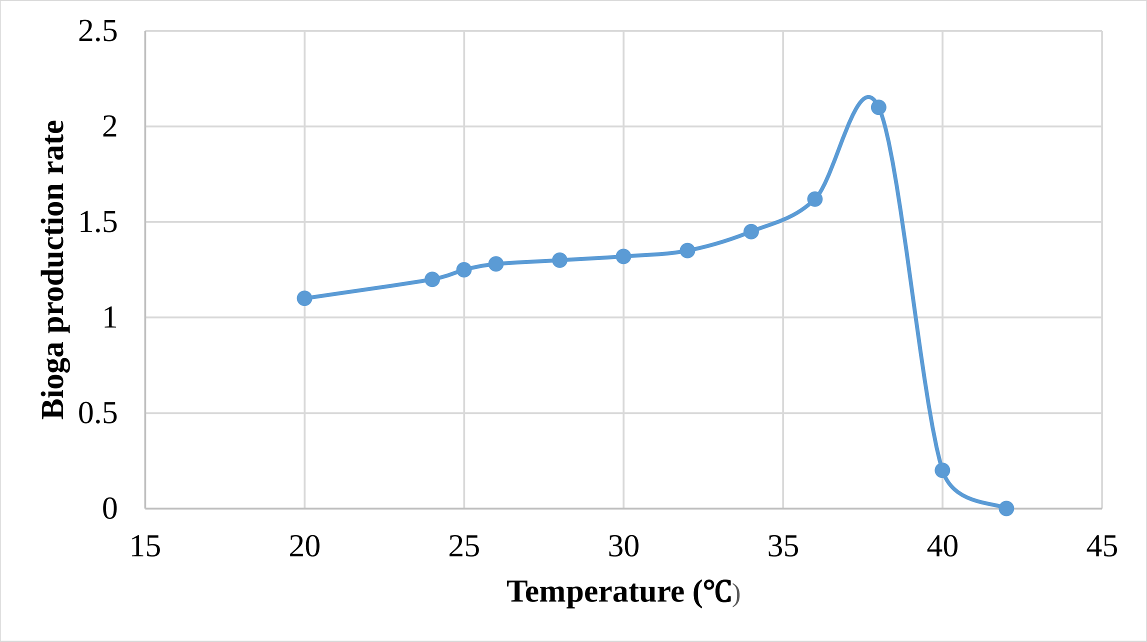

Figure 2.7: Biogas production rate versus temperature (Adapted from Sichilalu et al., 2017)

The graph shows an increase in biogas production rate and is assumed to be as a result of increased bacterial activity. Production rate stops increasing when the temperature goes beyond 40 degrees. Maximum production takes place at 38℃ hence, mesophilic temperatures should be kept within 37℃ to 39℃.

Ukpai et al. (2015) studied the effect of temperature on the rate of biogas production using cow dung, cow pea and cassava peeling. Three batch biogas plant having different mix ratios of the 3 substrates was used and biogas production was monitored for 30 days. The results showed that gas production depends on the temperature of operation of the digester and the nature of waste used. A temperature of the 32-40℃ range was reported to be favorable and optimum for an increase in gas production.

c) Mixing

Mixing ensures contact between micro-organisms, substrates, and nutrients and offers uniform temperature distribution in the digester. Adequate mixing also can lower sedimentation and foaming caused by floating fat with adhering gas bubbles or by filamentous micro-organisms, such as Microthrix or Norcadia (Barjenbruch et al., 2000). Reactors equipped with mixing tend to produce more biogas compared to those without (Karim et al., 2005). Mixing can be accomplished through mechanical (employing a mixer), hydraulic (liquid recirculation), and pneumatic (recirculation of gases) techniques (Wang et al., 2017) at various frequencies; continuously or intermittently several hours or several times in an hour during a day and intensities; gentle, intermittent, and rigorous rotation speed (Ward et al., 2008).

Employing intermittent mixing, mass transfer from the liquid phase to the gas phase is greatly enhanced causing an increased gas production as much as 70% higher than the periods without mixing (Ong et al., 2020). Gentle mixing is more effective as it leads to the formation of aggregates and prevents methane-producing organisms from being washed out by the liquid (Kaparaju et al., 2008).

Chaoui and Richard (2008) studied the effect of mixing frequency on biogas yield in anaerobic digesters in a lab batch anaerobic digester. Mixing frequencies; once, twice, thrice a day, mixing for a minute every time were used. Results revealed that increasing frequencies from one to three times a day significantly decreased biogas volume. It also reduced the rate of biological oxygen demand reduction.

d) pH

The pH value designates the digester's health since it affects methanogenic micro-organisms' growth. The tolerable range of pH for methane formation is from 5.5 to 8.5 (Seadi, et al., 2008). The requirement of anaerobic digestion bacteria differs. Acidogenic bacteria work best at pH 5 while methanogens best at 6.2. Methanogens are sensitive to acid concentration and their growth can be repressed (Kangle et al., 2011).

Acetogenesis occurs at a rapid pace and hence increasing the pH is essential. This can be achieved through the use of basic solutions like sodium hydroxide or potassium hydroxide. Also, degradation of protein through the release of ammonia has a buffering capacity as it can raise pH value to above 8. During methanogenesis, the concentration of ammonia rises and the pH value can increase to above 8. Therefore, a decrease in pH is necessary through the addition of lime or recycled filtrate gotten during residue treatment. The use of recycled filtrate eliminates the lime requirement (Opoku, 2011).

Jayaraj et al. (2014) examined the effects of pH on biogas production from food waste by anaerobic digestion. This was experimentally analyzed in five laboratory-scale batch reactors maintained at pH 5, 6, 7, 8 and 9 under thermophilic temperature conditions and a hydraulic retention time of 30 days. Higher gas yield and degradation efficiency were at pH 7 compared to others. The lowest biogas yield and degradation efficiency were with the substrate pH 5.

e) Retention Time

Retention time is the time needed for the complete depletion of a substrate. Depends on the composition of the feedstock, temperature, pH and particle size. The higher the total solid content in the feed the higher the retention time, favorable temperature ranges decrease the retention time and the smaller the particle's size the shorter the retention time due to high reaction rates (Monnet, 2003).

The shorter the retention time the greater the bacteria washed out in the digester than their replication (Gray, 2004). Table 2.1 shows the approximate retention time of substrate liquid manure undergoing anaerobic digestion under the mesophilic temperature range.

Table 2.2: Approximate values of Retention time of different liquid substrates

Substrate type	**Retention time(days)**
Liquid cow manure	20-30
Liquid pig manure	15-25
Liquid chicken manure	50-80

Source: Gray (2004)

f) Particle Size

Particle size influences the reaction rate. The reduced the particle size the higher the surface area to volume ratio and accordingly increased the reaction rate. This causes an increase in gas yield and reduction in residue amount which results in a retention time decrease. Also, particle size reduction permits the suspension of the particles that depresses the settling time and successively the flow of particles with the fluid (Perera, 2011).

Nalinga and Legonda (2016) reported the finely grounded substrate (0.001 mm) of pre-treated water hyacinth to have the highest biogas production of 0.39 liters with 70 % methane, followed by 0.05 mm with biogas yield of 0.34 liters with 66 % methane. The lowest biogas production was observed at 2.5 mm producing 0.24 liters of biogas with 55 % CH_4. Methane yields increased by 21 % when the substrates were pre-treated by grinding into very fine particles compared with the chopped substrate. Also, Hajji and Rhachi (2013) examined the influence of particle size (10 mm, 20mm, 30mm and 100 mm) on the performance of anaerobic digestion of municipal solid and recorded optimum production for small particle sizes.

g) Organic Loading Rates

The organic loading rate is the quantity of organic material added per unit volume of the AD reactor in a day and can be expressed as volatile solids or biological or chemical oxygen demand. OLR affects the rate of biogas production and maximum yield from the stated size of the AD digester, it has to be kept as maximum, but at the higher concentration, the AD process may be inhibited due to the accumulation of volatile fatty acids that may cause a decrease pH in the digester (Sahito et al., 2016).

Xie (2012) examined organic loading rate (OLRs, 1.0, 1.5, 2.0 and 3.0 kg VS/m^3/d) by setting up 3 liters continuously stirred tank reactors at various separated pig manure (PM) to dried grass silage (GS) volatile solid ratios. It was found that the OLR affected the digester performance more than the dried GS proportion in the feedstock. Increasing the OLR increased the volumetric methane yields by 88% but decreased the specific methane yields by 38%.

Perera (2011) investigates operating conditions for optimum biogas production in plug flow type digester. Three feed rates of 1.4kg, 3kg and 6kg were used under a retention time of 20 days. The highest specific methane production of 0.341 m^3/kg VS per day was observed at 1.4kg per day together with the highest VS reduction of 91.37%.

Phuong (2018) investigated the effect of substrate loading rate on anaerobic digestion using a composite biogas tank. The substrate was feacal sludge (FS) and organic waste (OW) mixed at a ratio of 3:1 respectively by weight. The fresh substrate was fed as a batch and kept for 30 days and the reactor was operated at three different loading rates of 1.0±0.1, 1.5±0.1 and 2.0±0.1 kg VS/m^3.day. When the loading rate increased from 1.0±0.1 to 1.5±0.1 kg VS/m^3.day the yield biogas also rises from 284 $*10^{-12}$ to 490.32$*10^{-12}$ m^3/kgVS of the feed with methane content higher than 60%. At 2±0.1 kg VS/m^3.day loading rate, biogas yield reduced to 236.11$*10^{-12}$$m^3$/kgVS of the feed with methane content lower than 50 %. The organic loading rate of 1.5±0.1kg VS/m^3day was then suitable for anaerobic co-digestion of feacal sludge and organic waste.

h) C/N Ratio

The optimal C: N ratio of substrates ranges between 20:1 and 30:1. When the ratio is less than the optimal it causes more formation of ammonia which results in inhibition when greater it results in increased consumption of nitrogen by microbial groups and this results in reduced biogas production during methanogenesis (Muzenda, 2014).

C/N ratio is a correlation between the amount of carbon and nitrogen in organic matter. If the ratio is high nitrogen will be depleted rapidly to meet nutrients requirements and will not further react on the remaining carbon thus resulting in low gas production. On the other, if the ratio is lower; nitrogen will be acted upon more rapidly resulting in ammonia accumulation which causes inhibition (Kavuma, 2013). The optimum C/N ratio should range from 20-30:1 because the micro-organisms utilize carbon 30 times faster than nitrogen (Ofoefule et al., 2010). The tuning of the ratio to within the optimum range of 25-30 can be achieved through co-digestion of different waste (Monnet, 2003). Table 2.3 shows the C/N ratio of different organic materials.

i) Inoculum

Fresh feedstocks have micro-organisms less than the required amount hence adequate inoculum must be added at the starting of the anaerobic digestion process. Bacterial cultures can be obtained from biogas-producing facilities or artificial cultures, cow dung and sewage manure (Perera, 2011). Increasing ratio of substrate to inoculum has an inverse trend to biogas production, substrate utilization and might induce process stability. Too little inoculum can cause drawbacks associated with VFA accumulation, incomplete feedstock degradation, inhibition and a slower methane production rate (Sarker et al., 2019).

Dennis (2015) investigated the effect of inoculums on biogas yield. Cow dung was used as the substrate and the rumen fluid as the inoculum. A 750ml bio digester was used and the water displacement method was used to measure the amount of biogas produced. 100g of fresh cattle manure was fed to each bio digester and mixed with rumen fluid and tap water in various ratios including 1:1:0, 1:0:75,0:25:1, 0:5:0, 5: 1:0, 25:0:75 and 1:0:1 respectively corresponding to 0, 12.5, 25, 37.5 and 50% rumen respectively. The operational temperature was at room temperature. The results revealed that biogas production increased with an increase in the inoculums' amount.

Asante-Sackey et al. (2018) evaluated the effects of inoculum to feedstock ratio on anaerobic digestion for biogas production. Five laboratory-scale bio-digesters were used for anaerobic co-digestion of Miscanthus Fuscus and cow dung. The tests were done at a pH range of 6.2-7.8, Mesophilic temperature of 35 ± 2˚C and in batch mode at a hydraulic retention time of 33 days. The anaerobic co-digestion process was carried out at varying inoculum to feedstock ratios of 1:0, 0:1, 1:3, 3:1, and 1:1. The highest biogas potential was recorded at an inoculum to feedstock ratio of 3:1 with the least biogas potential recorded by the bio digester at a ratio of 0:1.

j) Toxicity

Toxic materials such as mineral ions, heavy metals and detergents inhibit the normal growth of micro-organisms in the digester. A small quantity of mineral ions including sodium, potassium, calcium, magnesium, ammonium and sulphur stimulates the growth of bacteria, whereas a heavy concentration of these ions causes toxic effects. For example, the presence of NH_4 from 50 to 200 mg/l stimulates the growth of anaerobic microbes, whereas, its concentration above 1500 mg/l produces toxicity. Also, heavy metals such as copper, nickel, chromium, zinc, lead in small quantities are essential for the growth of bacteria but higher concentration has toxic effects. Detergents including soap, antibiotics, organic solvents also inhibit the activity of methane-producing bacteria and hence these substances in the digester should be avoided (Mahanta et al., 2005).

k) Additives

Additives play an important role in the biogas production rate. Adding a 5% commercial charcoal to cattle dung slurry on a dry weight basis elevated the yield by 17 and 35% in batch and semi-continuous anaerobic digestion processes respectively (Mahanta et al.,2005). The addition of inert materials such as vermiculite, charcoal and lignite bovine excreta as feed on biogas yield has also been reported to improve biogas production rate by 15-30%. Also, suspending pebbles, glass marbles and plastic mesh in a digester slurry was reported to have led to an increase in the gas yield by 10-20% (Mahanta et al., 2005).

2.5 Characterization of Feedstock

Various feedstock for anaerobic digestion includes; an organic fraction of municipal solid waste (OFMSW), sewage sludge, grass clippings/garden waste, food remains, manure (cattle, pig, poultry), energy crops, algal biomass, harvest remains and waste from food or beverage processing, dairy, starch industry, sugar industry, pharmaceutical industry, cosmetic industry, biochemical industry, pulp and paper, slaughterhouse/rendering plant (Steffen et al.,1998).

Anaerobic digestion feedstocks considerably vary in qualitative and quantitative composition, homogeneity, fluid dynamics and biodegradability. Table 2.4 represents the physiochemical characteristics of various animal manure.

Table 2.3: Feedstock characteristics

Animal manure	pH	TS (%)	VS (%)	C/N ratio	Reference
Cattle manure	7.1-8.6	14.5-22.7	11.9-72.0	14.59-18.9	Abubakar and Ismail (2012); Achinas et al. (2019); Li et al. (2020); Muatafa et al. (2016); Shen et al. (2019).
Pig manure	6.4-7.5	8.2-36.7	6.2-82.8	5.7-13.5	Duan et al. (2019); Ferrer et al. (2009); Ning et al. (2019); Rodríguez-Abalde et al. (2017); Shen et al. (2019); Wang et al. (2020); Xie et al. (2011).
Chicken manure	6.9-7.4	20.0-92.6	18.3-84.1	7.5-9.75	Bojti et al. (2017); Cheong et al. (2019); Li et al. (2018); Liu et al. (2015); Scarlat et al. (2018); Shen et al. (2019).
Sheep manure	7.16-8.1	22.3-40.0	18.7-72.7	11.3-14.7	Achinas et al. (2018); Li et al. (2020); Zhang et al. (2013).
Goat manure	7.9	33.7-55.5	27.7-89.4	18.0	Achinas et al. (2018); Imeni et al. (2019); Zhang et al. (2013).
Donkey manure	6.8	19.8	14.4	-	Mukumba et al. (2016).

2.5.1 Cow Dung

Cow dung (CD) is a favorable substrate for co-digestion since it has nutrients such as metals, vitamins and other compounds necessary for microbial growth. Also, it neutralizes pH and has high water content which helps to dilute the concentrated organic wastes (Gashaw & Teshita, 2014). Characteristics of the manure are; 53.92% organic carbon, 2.24 % total nitrogen, 24.10 C/N ratio, 0.48% potassium, 0.57% potassium, 5.40% nitrate ion, 107 mg/kg zinc, 18.70mg/kg copper, 147.6mg/kg manganese 8.50 pH, 0.84 % sodium, 0.53% calcium, 21.90mg/kg lead 9.29% ash (Adelekan & Bamgboye, 2009).

Cow dung also is helpful at the start fermentation phase as it contains methanogenic bacteria necessary for the process. Anaerobic digestion of cow manure alone produces less methane due to moderate biodegradable materials of about 45-50% (Rico et al., 2007). Furthermore, cow manure yields less biogas because of the presence of left-over lignin complexes from fodder which are resistant to anaerobic digestion (Monteiro et al., 2011). Cattle manure biodegrades slowly compared to other organic waste. Improvement of biodegradability and VS of the reactor can be achieved through co-digestion of cattle waste with food waste, fruit or vegetable waste, industrial organic waste or sewage sludge (Tufaner & Avsar, 2016).

2.5.2 Pig Manure

Anaerobic digestion of pig manure has benefits over its traditional management; methane gas production which replaces fossil fuel, improvement of fertilizing abilities, pathogen reduction, decreased odor and improved flow characteristics (Ward et al., 2008). Table 2.5 summarizes the properties of pig manure.

Table 2.4: Properties of pig manure

Parameters	Value range
Total solids (TS), %	0.78-9.95
Total volatile solids (TVS), %	0.30-8.16
Total Kjedal nitrogen (TKN), mg/l	1217-6698
Chemical oxygen demand (COD), mg/l	540-3875
Ammonium nitrogen (NH_4^+-N). mg/l	7138-174300
Soluble COD,mg/l	1112-74700
5-day biochemical oxygen demand (BOD_5), mg/l	702-23600
Total phosphorous (P), mg/l	352-2720
Total potassium (K), mg/l	
Ph	7.01-7.91

Source: Martinez-Suller et al. (2008); Masse et al. (2007); Moral et al. (2005); Scotford et al. (1998); Vanotti et al. (2007); Zhu et al. (2006).

2.5.3 Sheep Manure

Properties includes; 2.59% nitrogen, 29.28 carbon to nitrogen ratio, 3.85% hydrogen, 0.70 sulphur, 17.17 % oxygen, 46.42 ash, 15.1% moisture content and 7,68 pH (Nagy et al.,2018). Anaerobic digestion of sheep manure needs a longer hydraulic retention time and produces less biogas when associated with other farming manure with comparable chemical characteristics, such as pigs, poultry, and cattle manure (Cestanaro et al., 2015).

Achinas et al. (2018) reported the influence of sheep manure addition on biogas potential and methanogenic communities during cow dung digestion under mesophilic conditions. The aim was to examine how the co-digestion of sheep manure and cow dung by not using inoculum influences the performance of the process and determine the methanogenic communities. Higher biogas production was achieved from the mono-digestion of cow dung and the co-digestion of cow dung and sterilized sheep manure. Sheep manure results in less gas yield compared to cow manure. Moreover, it causes less biogas production compared to when co-digested with cow dung. Less biogas yield is a result of anaerobic digestion inhibition caused by the inactivity of sheep manures' micro-organisms.

2.5.4 Chicken Manure

Chicken manure encompasses high amounts of biodegradable organic matter. Anaerobic digestion is an option to treat and stabilize the organic matter in it along with biogas production. It comprises 25.3% total solids, 17.93% volatile solids, 47.4 g/kg of total Kjeldahl nitrogen and 0.64 g/kg of total sulfur contents (Molaey et al., 2018).

It has high nitrogen content which causes ammonia inhibition making it a challenge in anaerobic digestion (Bujoczek et al., 2000; Gangagni et al., 2008). To enable chicken manure used as single manure, it has to be stripped off into the gas phase through evaporation. A mix ratio of 3:2 of chicken manure with cattle dung with a C/N ratio of 27.2:1 yields maximum methane (Nie et al., 2015).

2.6 Comparative Studies of Biogas Production of Different Substrates

2.6.1 Biogas Production Rate of Animal Manures

From the research done different substrates have different biogas production rates;

Table 2. 5: Biogas production rates (m^3/kg VS)

Materials	Total solids (%)	Volatile solids (%)	Retention time (days)	Biogas yield
Pig manure	3-81	70-80	20-40	0.25-0.50
Cattle dung	5-12	75-85	20-30	0.20-0.30
Chicken manure	10-30	70-80	>30	0.35-0.60
Sheep manure	-	-	-	0.30-0.61
Cow dung: pig manure	-	-	-	0.35

Source: Ertem (2011); FAO (1997); Sibiya et al. (2017)

Comparing biogas production for the six different animal dungs (sheep, chicken, pig, goat, cow and horse), 50 g dry weight of each animals' dung were weighed, put in separate 1-liter aspirator bottles. Tap water was added to make the volume a little above 1-litre and was stirred manually. Sheep dung lead with an average of 1.15L biogas produced in 8 weeks, followed by chicken (1.03L), pig (0.65L), goats (0.45L), cow (0.17L) and the horse was least with 0.03 L. (Olowoyeye, 2013).

Aremu and Agarry (2012) studied separately the anaerobic digestion of cow and pig dung using cow rumen as a source of methanogens. 8% total solids, 27 – 35 °C temperature range and a pH range of 6.2-6.8 were maintained in this study for 30 days. The displacement method was used to measure biogas produced during the process. A cumulative average biogas volume of 4140 ml (138 ml day) was recorded for cow dung while pig dung gave a cumulative average biogas volume of 4378 ml (145.9 ml day).

2.6.2 Effects of Co-digestion on Gas Yield

Co-digestion shows improvement in biogas production from the studies with advantages being; inexpensive, causes a reduction in the concentration of toxic compounds, settled demand of nutrients, synergistic effects of anaerobic bacteria, improved biodegradable substrate loading, hygienic stabilization and improved rate of digestion (Sosnowski *et al.,* 2003). It also resolves any pH, alkalinity, macro-nutrients and micronutrients elements imbalance (Amon et al., 2007).

Co-digestion of wastes rich in proteins provides buffering and ensures the availability of nutrients while one with high carbon content balances the C/N ratio decreasing the risk of ammonia accumulation (Hashimoto, 1986; Hills & Roberts, 1981). Table 2. 6 shows the methanogenic ability of co-digestion of different feedstocks.

Table 2.6: Methanogenic ability of co-digestion of different feedstocks

Feedstocks	Mix ratio (%)	Biogas(L/kg)	Increase in biogas production
Sewage sludge + grasses	50:50	387	+42%
Birds manure +grasses	50:50	513	+13.5%
Birds manure +sewage sludge	50:50	495	+12.3%
Cow manure + pigs + birds	25:50:25	585	+9.6%
Pig manure +birds	50:50	634	+7%
Cow manure + grasses	50:50	363	+5%
Cow manure + sewage sludge	50:50	407	+26%
Cow manure + birds	50:50	528	+6%
Cow manure + pigs	50:50	510	+7.5%

Source: Singh et al. (2017)

Muyiiya and Kasisira (2009) compared the effect of mixing pig and cow dung on biogas yield. Mix ratio 1:1 of cow dung and pig manure respectively showed the greatest biogas production followed by 1:3, then 3:1, then 0:1 and lastly 1:0. The highest gas yield from mix ratio of 1:1 was attributed to stable pH and it was hypothesized that the mixture was able to buffer itself; a pre-requisite for proper biogas production.

Ngunjiri et al. (2015) investigated the rate and quality of biogas generation by co-digesting cow dung with sheep droppings (CS) and cow dung with chicken droppings (CC) compared to cow dung alone (CA). 11 units, 20litres containers were used for the anaerobic digestion. The substrates were diluted with water to attain 11% total solids. All mixture ratios of CS and CC (9:1, 7:3, 1:1, 3:7 and 1:9) were reported to have shown improvement in biogas generation and quality compared to CA alone. The mixture ratio of 7:3 for CC and CS recorded the highest biogas production of 17.0 and 13.3 m^3 respectively with a retention time of 28 days compared to 6.0 m^3 for CA. Significantly improvement for biogas quality was observed for CC and CS for the ratios 3:7 and 1:9 with methane contents above 64% for CC and above 62% for CS.

Pure pig manure produced more gas per unit weight as compared to pure cow dung as seen in the findings described above. This agrees with Hobson's et al. (1981) findings that attributed the lower biogas production to low biodegradable material in the cow dung. Yeole et al. (1992) attributed the higher biogas yield from the pig dung to the presence of native micro flora in the pig dung. Fulford (1988) attributed it to the low carbon-nitrogen ratio and the higher production from the mixtures reported that it could be due to a proper nutrient balance.

2.7 Principal Component Analysis

2.7.1 Definition

Principal component analysis (PCA) is a multivariate technique that analyzes data described by several inter-correlated dependent variables to extract the important information to represent it as a set of new orthogonal variables called principal components. It is mostly used as a tool in exploratory data analysis and for developing predictive models (Abdi & Williams, 2010). It has been used to distinguish instability periods and also different process performance or waste compositions (Reed et al., 2011); to monitor industrial processes (Li et al., 2000) and in wastewater treatment processes (Lee & Vanrolleghem, 2004).

PCA can be achieved by determining the eigenvalue of a data covariance matrix or singular value decomposition of a data matrix after the standardization step of the initial data. Standardization of each element is achieved by subtracting each data value from the mean so that its empirical mean is zero and probably standardizing each variable’s variance to make it equal to 6 as described by equation 2.6 (Abdi & Williams, 2010).

$$z = \frac{x - \mu}{\sigma} \tag{2.6}$$

Where μ is the mean of the data and σ is the standard deviation of the data. Mean centering (mean subtraction) is done to ensure that the first principal component defines the direction of maximum variance. Failure to do so, the first principal component instead might resemble the mean of data and hence a mean of zero is required to minimize the mean square error of the data (Miranda et al., 2007).

2.7.2 Application of PCA

According to Reris and Brooks (2015), applications of PCA include dimensionality reduction, regression, ranking and total least squares regression. Dimensionality reduction can be achieved by creating a set of derived variables called the principal components that are a linear combination of the original variables. Principal component regression can be achieved by first performing the PCA then regress it on the derived variables using the scores to get a model of the form;

$$y = \alpha + z\beta \tag{2.7}$$

Where,

y is the dependent variable

α is an intercept

β is a coefficient.

Ranking can be accomplished by combining the characteristics into a single measure that ranks the parameter. First principal component scores are used in ranking because it is the direction along which the measurements are heavily loaded. The variable that tends to have the largest score tend to be those that result in high parameter. Moreover, total least squares regression can be attained through the building of a model to predict one of the characteristics of a particular variable using other characteristics.

Nikiema et al. (2017) optimized biogas production from the organic fraction of municipal waste. Cow dung and waste water were used as inoculum with different mixtures as 1:9, 3:7, 1:1, 7:3 9:1 1: and 0:1 respectively. The inoculum was also enriched with cellulose at 5% (w/v). Principal Component Analysis (PCA) was done to reduce geometric space and visualize data by use of a linear combination of variables that maximizes variance. The method neither permits visualization of the typology of the different combinations but also avoids the redundancy of the variables by considering the study in the reduced space of uncorrelated. Combination 1:1, 1:9 and 3:7 were reported to have a significant production of biogas, 0:1, 1:9 and 3:7 had a high proportion of methane while 7:3 had a high proportion of carbon dioxide.

Leite et al. (2017) used PCA to compare single and two-stage anaerobic digestion (AD) process performances when treating waste-activated sludge (WAS) to increase their monitoring and control. Two experiments considered single and two-stage AD using WAS and fermented WAS as substrates were carried out to compare the current results with outcomes of univariate analysis. PCA exposed some significant differences between the two experiments; AD of fermented WAS showed higher Specific Methane Production, higher partial alkalinity concentration and a lesser concentration of VFA. These outcomes confirm the superior performances of the AD of fermented WAS compared with the AD of WAS.

2.8 Optimization of Biogas Production

Optimization is the performance of attaining the best possible outcome under given conditions. It is the process of finding conditions that give the minimum or the maximum value of a function (Astolfi & Praly, 2006). Anaerobic digestion optimization is one of the ways of improving the productivity of biogas power plants (Wolf et al., 2009). According to Balaji et al. (2013) simplex method response surface method (RSM), genetic algorithm (GA), artificial neural network (ANN), Taguchi method and gray relational analysis (GRA) are the most common and widely used techniques to optimize the parameters.

2.8.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical techniques suitable for designing and characterizing the relationship between a response and a set of variables or factors of interest to the researcher and determining the optimum conditions for the desired response. The data obtained from an experiment are used to draw inferences about the process under study (Valdez- Vazquez et al., 2015).

Shehu et al. (2012) optimized thermo-alkaline disintegration of sewage sludge to enhanced biogas yield using response surface methodology (RSM) and Box–Behnken design of experiment. The individual linear and quadratic effects as well as the interactive effects of temperature, sodium hydroxide (NaOH) concentration and time on the degree of disintegration were investigated. The optimum degree of disintegration achieved was 61.45% at 88.50 ℃, 2.29 M NaOH (24.23% w/w total solids) and 21 min retention time.

Deepanraj et al. (2020) optimized biogas production from food waste through anaerobic digestion using response surface methodology. The chosen process parameters include solid concentration (5-15%), pH (5-9), temperature (30-60℃) and co-digestion (0-40%) of poultry manure. The solid concentration of 7.38%, pH value 7, 48.43℃ and co-digestion a 29% were observed to be the optimal levels.

2.8.2 Genetic Algorithm Optimization Technique

A genetic algorithm is a type of optimization tool. It symbolizes evolutionary computation by imitating the biological processes of reproduction and natural selection to resolve for the fittest results (Carr, 2014).

Abu et al. (2010) applied an Artificial Neural Network (ANN) and Genetic Algorithm (GA) to simulate and optimize the digester’s biogas production process. The ANN model was trained to simulate the digester operation incorporating the effect of digester parameters namely temperature, non-volatile solids and volatile solids, and PH. The operational plant data from a period of 177 days was used. The GA optimized and predicted the methane production with a 0.87 correlation coefficient of effectiveness. The modeled methane production from the obtained optimal operating conditions increased by 6.9 %.

Kana et al. (2012) developed an Artificial Neural Network to model the biogas production on mixed substrates of saw dust, cow dung, banana stem, rice bran and paper waste. The genetic Algorithm later was use to optimize the model's process and the model was the fitness function. The data used to train and validate the ANN model were taken from twenty-five mini-plot biogas fermentations. A predicted biogas performance of 10.144L was provided using the optimized substrate profile while its evolution gave a biogas production of 10.280L increasing its performance by 8.64%.

2.8.3 Full Factorial Design

According to Thompson (2009), a full factorial experiment is one whose design consists of two or more factors each with a distinct level and whose experimental units take all possible combinations of those levels across all factors. It allows to study the effect of every factor and also the effects of interactions between factors on the response variable. Full factorial experiments are favored where there is a small number of variables having strong interactions between them.

Alhassan et al. (2016) used a full 4^2 factorial experimental design procedure to optimize parameters in biogas production from cow dung using a laboratory size anaerobic digester. The parameters included production temperature, residence time and the yield of biogas. The results showed that biogas yield is dependent on production temperature, residence time and the interaction of the two. The full mathematical model was developed which includes the two main effects and interaction. The optimizer plot suggested that to optimize biogas production rate, the experiment should be conducted at 60°C temperature and 5 days residence time.

Nkodi et al. (2020) investigated factors affecting biogas production from cassava peels by fractional Factorial Design Experimental Methodology. The parameters studied were initial pH, organic loading rate, particle size and co-substrate type. Eight biodigesters (TH_1, TH_2, TH_3, TH_4, TH_5, TH_6, TH_7 and TH_8) in duplicate were used for the anaerobic digestion of cassava peels. The tests results showed that organic loading rate (X_2), particle size (X_3) and co-substrate (X_4) had a significant effect on the biogas production rate. The full mathematical model was developed including two main effects (X_2 and X_3) and three interactions (X_1X_2, X_2X_3 and $X_1 X_2 X_3$). Digester TH_2 produced the highest biogas volume of 2252mL obtained under the following conditions: initial pH 7.8, 5% TS, ≤2 mm of particle and urea as co-substrate, while digester TH_8 had a somewhat low biogas yield of 2129.5ml. It was then concluded that the best conditions to produce biogas from cassava peels are those of TH_2.

2.8.4 The Taguchi Optimization Technique

The Taguchi method is a statistical approach that was developed by Taguchi and Konishi to optimize process parameters and improve the quality of components that are manufactured(Athreya &Venkatesh, 2012).

The technique is divided into three stages: system design, parameter design, and tolerance design. System design involves the input of scientific and engineering information needed for producing parts or coming up with process parameters. Contrary, the tolerance design helps to determine and to analyze tolerances about optimum combinations suggested by parameter design. Parameter design helps to obtain optimum levels of process parameters for developing the quality characteristics and determine product parameter values depending on optimum process parameters (Oktem et al., 2007). Figure2.8 describes the steps involved in the Taguchi design method.

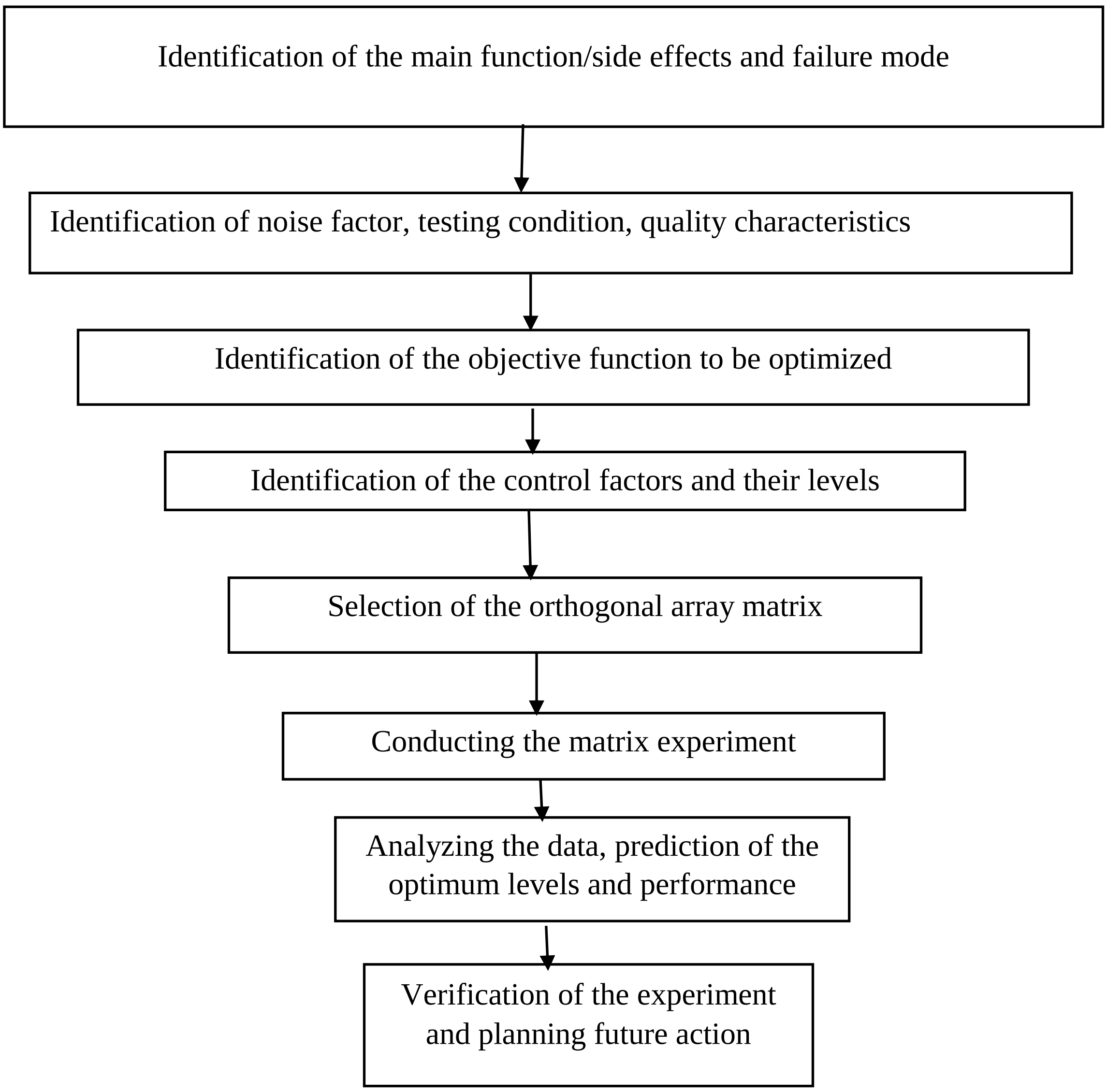

Figure 2.8 Flowchart showing steps of Taguchi approach

The design method uses an orthogonal array (OA), Signal- to- noise(S/N) ratios, main effects and analysis variance (ANOVA). An orthogonal array is a matrix of numbers arranged in rows and columns. Each column indicates a value of a factor and each row represents a set of parameters for one run of the experiment. It provides a set of least experiment runs while S/N are logarithm function for optimization (Datta et al., 2008). According to Athreya and Venkatesh (2012) selecting the correct orthogonal array to be used is achieved by using the equation of the form;

$$N = P\ (L\ -\ 1)\ +1 \quad (2.8)$$

Where N is the minimum number of experiments, L is the number of levels and P represents the number of parameters.

S/N ratio is used to identify quality characteristics applied for engineering design problems. The S/N ratio characteristics are divided into three steps: the smaller the better, the nominal the better, and the larger the better (Wu & Wu, 2000). Thus, S/N measures the quality based on reduction of variation during processing while orthogonal array accounts for the number of experiments. Based on the ratio characteristic desired, the following equations are used to determine the S/N ratio values for a better determination:

a) For the nominal the better;

$$S/N = 10\log\frac{\bar{y}}{s_y^2} \quad (2.9)$$

b) For the smaller the better;

$$S/N = -10\log\frac{1}{n}\left(\sum y^2\right) \quad (2.10)$$

c) For the larger the better;

$$S/N = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad (2.11)$$

Where,

n is the total samples

y is the individual sample observation.

The above equations are used selectively depending on the objective of the optimization being done. Main effects and ANOVA are done after statistical analysis of the S/N ratio. The main effect is used to determine the optimal combination of operating process parameters while ANOVA is used to evaluate the error variance and to determine the significance of the selected parameters (Fei et al., 2013).

Ravella et al. (2008) optimized biogas of production using Taguchi methodology for five parameters which include pre-hydrolysis (without and with), temperature (35 and 40℃), substrate concentration w/v (4 and 6%), inoculum (15 and 30% v/v) and stirring (continuous and on (8 hours a day) and off). The results showed that the optimum condition requires no pre-hydrolysis, with 6% w/v pig feed, at 35℃, with high inoculum concentration and with continuous stirring.

Balaji et al. (2018) optimized anaerobic digestion of poultry litter using Taguchi Grey Analysis four factor-four level Taguchi design under experimental conditions including pH (7.2-7.8), temperature (25-28℃), solid concentration (9.5-21.5%) and C/N (15.1-15.4). obtained optimum levels were solid concentration of 13.5% TS, pH of 7.4, the temperature of 26℃ and C/N of 15.3.

Said et al. (2013) made a comparison between response surface methodology (RSM)and Taguchi method to optimize machining conditions for aluminum-silicon alloy and found that the Taguchi method required a smaller number of experimentations than RSM and accurately optimized machining condition.

Youssef et al. (1994) compared full factorial design, fractional factorial design and Taguchi design. It was found that Taguchi's design was sufficient for screening process parameters and able to lessen experiments from 288 trials of full factorial design to 16 trials only. The data analyzed by the Taguchi method was reliable and more economical than the full factorial design.

From the literature reviewed, it is evident that limited studies have been carried out on the influence of mix ratios, total solids and feeding rate on biogas production on anaerobic digestion of cow dung, sheep manure and pig manure. Few attempts have also been made to optimize the parameters affecting biogas production using the Taguchi technique. This study, therefore, hopes to fill in these knowledge gaps.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Characterization of Selected Mix Ratios of Cow to Pig to Sheep Manures

3.1.1 Selection of the Mix Ratios

Cattle, pig and sheep manures were chosen to be used in the research as the feedstocks for digestion due to their abundance availability at Tatton Farm, Egerton University. The manures mixed at varying ratios based on the recommendations by Levi and Dorothy (2009) that ratio of 1:1 of pig manure to cow dung and by Ngunjiri et al. (2015) that ratio of 7:3 (approximately 2:1) sheep manure to cow manure that gave the highest biogas yield. Ten mix ratios (by mass) namely 1:1:1, 3:1:1, 1:3:1,1:1:2, 2:1:1, 1:2:1, 1:1:2, 1:3:3, 3:3:1, 3:1:3 of cattle, pig and sheep manures, respectively, were selected to cover the range suggested by the two researchers with the three manures.

3.1.2 Characterization of the Mix Ratios

Laboratory analysis was done to determine the biophysical characteristics of the ten mix ratios of cow dung, pig manure and sheep manure. The total solid (TS), pH and volatile solid (VS) were determined according to APHA standard (APHA, 2005), total nitrogen was estimated by Kjedahl method (Greenberg et al., 1992) and the carbon content was determined by Walkey black method. Results are in Table 4.1.

3.1.3 Principal Component Analysis of Manures Characteristics

The total solids, carbon/nitrogen ratios, pH and volatile solids described in table 4.1 (except that of pure feedstocks) were subjected to principal component analysis. A MATLAB R2013a (8.1.0.604) mathematical software was used to determine the principal component coefficients (Tables A3.1), respective latent and scores (Tables A3.1). It was also used to project the original data in the space of both the three principal components and the first two principal components (Figures A3.1 and A3.2 respectively). MATLAB scripts used to attain the results are described in Appendix A1.2. Scree plotting (Figure A3.3) helps in the selection of the component that was used in the analysis. Principal component 1 was used for analysis as it was the direction along which the measurements were most heavily loaded (91%).

3.2 Effect of Mix Ratios, Total Solids and Organic Loading Rates on Biogas Production Rate

3.2.1 Laboratory Bioreactor

Anaerobic digestion of cattle manure, pig manure and sheep manure was done using a 0.15m³ laboratory digester (Figure 3.1). The photos of individual bioreactor components are presented in Appendix 2 as Plates A2.1 to A2.3.

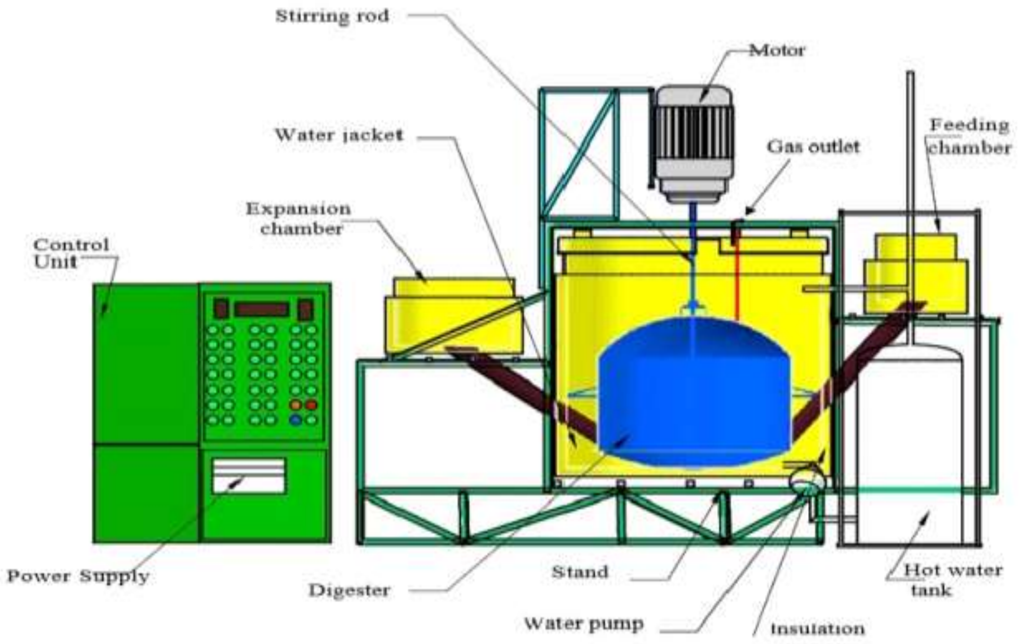

Figure 3.1: Fixed dome laboratory bio-reactor used for the research

The substrate from the feeding hopper was fed through the inlet pipe into the bioreactor. The substrate was stirred by the stirrer attached to the stirring rod with the help of an electric motor. This enables breaking of the scum and mixing of the substrate to acquire uniform distribution of temperature and bacteria. During gas production, pressure increases and this forces the substrate to be displaced into the expansion chamber. To reduce the pressure a gate valve was opened to allow the gas to escape through the gas delivery pipe. The gas then flowed into the inverted graduated cylinder filled with water and the water was displaced into the bucket. Digester temperature was regulated by the water that is heated by immersion electric heaters in a water tank and circulated by a centrifugal pump. A power supply provided electricity for water heating and to the control unit, the system for heating the water and monitoring the temperature. A computer was connected to the data logger which was connected to the thermocouple wires in the control unit to provide real-time temperature readings.

The temperature was maintained with the help of the partial integrals differential (PIDs) and program logic controls (PLCs) in a control panel. The immersion heaters heated the water in the water tank which then was circulated with the centrifugal pump. A thermostat regulates the immersion heaters by stopping the heating when the desired temperature was attained and switching them on when the temperature dropped.

3.2.2 Effect of Mix Ratio on Biogas Production Rate

Anaerobic digestion of the mixtures 1:1:3, 1:1:2, and 3:1:3 of cattle: pig: sheep manures as selected via PCA and pure manures were carried out. Water was added to the manures to attain a total solid of 8%, then fed to the digester until substrate started coming out of the exit pipe into the expansion chamber. The tests were set to run at 35±1ºC temperature being achieved by the PLC and PID control systems. Daily biogas yield measurement started as soon as the biogas started burning (an indication that the methane content was above 50%). The fresh substrate was daily fed starting from the 8th day of the digestion to the 19th day (3kg VS/m^3 day organic loading rate). From the control experiment done, gas production was found to peak on the 8th day and starts dropping as from day 9. Hence, to avoid falling of biogas production feeding of the fresh substrate into the digester starts from day 8 onwards. Every experiment was conducted for 20 days operation time and the biogas produced was measured by water displacement method. The data is presented in Table 4.4.

3.2.3 Effect of Varying Total Solids on Biogas Production

Based on Balsam and Ryan (2006), Budiyono et al. (2010) and Ngunjiri et al. (2014). different total solid of 6%, 8%, 10% and 12% were chosen for anaerobic digestion of the mix ratio 1:1:3 of cattle manure, pig manure and sheep manure at 35±1ºC digestion temperature. Fresh substrates were daily fed starting from the 8th day of the digestion when the biogas production started to decline to the 19th day at a 3kg VS/m^{3}day organic loading rate. Each test run for 20 days and biogas produced was daily measured by the water displacement method starting from the day the gas burns and the data is presented in Table 4.5.

3.2.4 Effect of Varying Organic Loading Rate on Biogas Production

An optimum range for the organic loading rate (OLR) is 2.5-3.5 kg VS/m^3 day and varies depending on the solid retention time and hydraulic retention time of the reactor (Kinyua, 2013). Based on this report, organic loading rates (OLR) 1kg VS/m^3 day, 2kg VS/m^3 day, 3kg VS/m^3 day and 4kg VS/m^3 day were selected. Semi-continuous anaerobic digestion of the four OLR were carried out using a mix ratio of 1:1:3 of cattle manure, pig manure and sheep manure, respectively, based on mass. The tests were carried out under 35±1ºC temperature and 20 days

Digestion period. Daily recharging started from day 8 of the digestion (when the biogas was observed to start decline) up to the 19^{th} date. Biogas produced was measured daily by the water displacement method starting from the day the gas burns. The results obtained are presented in Table 4.6.

3.3 Optimization of Biogas Production Parameters

Taguchi approach was used to find the optimum combination of total solid, organic loading rate and mix ratio in terms of maximum biogas production rate. Based on recommendations by Ngunjiri et al. (2014) of total solids of 8 to 12% and Kinyua (2013) of organic loading rate of 2.5-3.5 kg VS/m^3day as an optimum range for biogas production, three levels for total solids and three levels for organic loading rate were selected for the research. For the mix ratios, the obtained three top-ranked mix ratios obtained in the objective were chosen as given in Table 3.1.

Table 3.1: Digestion Process Parameters and their Levels

Factor	Parameter	Units	Level 1	Level 2	Level 3
A	Total solid	%	6	8	10
B	Organic loading rate	Kg VS/m^3day	2	3	4
C	Mix ratio		1:1:3	1:1:2	3:1:3

The selection of the orthogonal array for the Taguchi technique was made according to Athreya and Venkatesh (2012):

$$\text{Minimum number of experiments} = P(L - 1) + 1 \quad (3.1)$$

Where,

L = the number of levels and

P = the number of parameters.

$\therefore$ Minimum number of experiments = 3(3 - 1) +1

= 7

Therefore, the L_9 orthogonal array of the Taguchi method (Table 3.2) was chosen for this study.

Table 3.2: L_9 orthogonal array

Experiment No.	TS (%)	OLR (Kg VS/ m^3 day)	Mix ratios
1	6	2	1:1:3
2	6	3	1:1:2
3	6	4	3:1:3
4	8	2	1:1:2
5	8	3	3:1:3
6	8	4	1:1:3
7	10	2	3:1:3
8	10	3	1:1:3
9	10	4	1:1:2

The experiments were carried out using a 0.15 m^3 laboratory digester, under a constant temperature of 35±1ºC and an operation time of 20 days. Daily feeding of the digester was done starting from day 8 for every experiment. The biogas yield was measured daily by the use of the displacement method. S/N ratio was calculated using equation 2.3 applying the larger the better criterion. The mean S/N values for each parameter level were then calculated and used to determine the optimal combination of total solid, feeding rate and mix ratio for maximizing the biogas production rate. See optimization results in Figures 4.7, 4.8 and Appendix 5.

3.4 Data Analysis

Principal component analysis was used to rank the characterized mixtures of cattle to pig to sheep manures. The data obtained from the experiment were subjected to graphical and statistical analysis of variance (ANOVA) where degrees of freedom, sums of squares and mean sums of squares were calculated. The levels of significance between the factors were determined using the F-test. The treatment means that were different at 5% levels of significance were separated using least significance difference (LSD) according to Gomez and Gomez (1984). Taguchi technique was analyzed using the larger the better criterion and customized into Microsoft 2013 excel for analysis. Analyzed data are presented in chapter 4, appendix 3 and 4.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Characterization of the Mix Ratios

The mean values of the selected four biophysical characteristics as determined by the established protocols, namely total solids content, carbon-nitrogen ratio, pH and volatile solids of the pure cattle, pig and sheep manures and their various mix ratios are summarized in Table 4.1.

Table 4.1: Characteristics of different mix ratios of un-digested manure

Mix ratio	**Total solid content (%)**	**Carbon to Nitrogen ratio**	**pH**	**Volatile solid content (%)**
Cattle manure (pure)	19.18^{g}	23.68^{e}	6.50^{e}	88.37^{a}
Pig manure (pure)	23.50^{e}	13.27^{j}	7.90^{a}	84.57^{b}
Sheep manure (pure)	30.35^{a}	29.00^{a}	7.00^{d}	80.00^{e}
1:1:1	24.34^{d}	22.42^{g}	7.13^{cd}	84.31^{bc}
3:1:1	22.28^{f}	23.45^{d}	7.57^{b}	85.94^{b}
1:3:1	24.01^{de}	18.76^{k}	7.19^{cd}	82.59^{d}
1:1:3	26.75^{b}	25.05^{b}	7.26^{cd}	84.42^{bc}
2:1:1	23.05^{ef}	23.07^{f}	7.40^{bc}	85.33^{b}
1:2:1	24.13^{de}	20.13^{j}	7.26^{cd}	83.24^{cd}
1:1:2	25.85^{c}	24.07^{c}	7.30^{bc}	84.38^{bc}
1:3:3	25.82^{c}	21.68^{h}	7.30^{bc}	83.15^{cd}
3:3:1	22.63^{f}	20.54^{i}	7.29^{c}	84.24^{bc}
3:1:3	24.58^{d}	25.04^{b}	7.30^{bc}	85.55^{b}
LSD	0.80	0.17	0.29	1.55

Means followed by the same letter(s), (a, b, c, d, e, f, g), are not significantly different at $\alpha = 0.05$

4.1.1 Total Solids

The total solids content of pure cattle, pig and sheep manures were found to be 19.18%, 23.50% and 30.35% respectively, which slightly varied with reported values of 16.28%, 12.6%

and 27.78% respectively (Jha et al., 2012; Ngunjiri et al., 2014; Xie, 2012). The difference in the average values for the three feedstocks could be due to differences in aspects like; animal diet, manure collection and handling systems and other by-products added to the manure stream like feathers, blood and urine (Wang et al., 2019).

Upon mixing the three feedstocks at various mix ratios total solid content varies from 22.28% to 26.75%. Pure sheep manure had the highest value of 26.75%, which was significantly higher than those of cattle manure and pig manure alone and other ratios at the 0.05 level of significance. The recommended value for biogas digester slurry is between 8 to 12% (Ngunjiri et al., 2014). Thus, the manures were diluted with water to the required consistency before being introduced into the digester.

4.1.2 Carbon to Nitrogen Ratio

The C/N ratio of pure cattle, pig and sheep manures obtained were 23.68, 13.27 and 29.00 respectively, these results slightly varied with reported values of 24.3%, 22.1% and 24% respectively (Baek et al., 2020; Cestonaro et al., 2015). This variation could be due to the chemical properties of the animal feeds they consume. For instance, increased protein in the food causes an increased Nitrogen excretion (ASAE, 2005).

Mixing the three manures at various mix ratios causes the carbon to nitrogen ratio to range from 18.76 to 25.05. These values were significantly different at $\alpha=0.05$. The decisions on the ratio between feedstocks have been associated with optimization of carbon to nitrogen ratio and also the right combination of the several other parameters in the mixture such as macro and micronutrients, pH and alkalinity, inhibitors and toxic compounds, biodegradable organic and dry matter (Mata-Alvarez et al., 2014). This agrees with the results presented in Table 4.1. Mixing cattle, pig and sheep manures at varying mix ratios enable their C/N ratios to fall within the recommended range which is between 20:1 and 30:1 (Muzenda, 2014) except that of mix ratio1:3:1 (C/N ratio 18.76).

4.1.3 pH

The pH values of pure cattle, pig and sheep manures obtained were 6.50, 7.90 and 7.00. Mixing the three manures at various mix ratios causes the values to vary from 7.13 to 7.56, falling within the tolerable range for methane formation which is from 5.5 to 8.5 according to Seadi et al. (2008). Pure manure had the highest value of 7.90 and pure cattle manure had the lowest value of 6.50. Values for mixtures 3:1:1, 3:1:3,1:3:3,1:1:2 were not significantly different at LSD=0.29 as well as that of 2:1:1, 3:3:1, 3:1:3, 1:3:3, 1:1:2, 2:1:1, 1:1:1, 1:3:1,1:1:3 and 1:2:1

4.1.4 Volatile Solids

The volatile content obtained was 88.37%, 84.57% and 80.00% of pure cattle, pig and sheep manures respectively. It's evident that mixing the three feedstocks at varied mix ratios also results in varied VS content. The values obtained ranges from 85.94% to 82.59%. Cattle manure had the highest value of 88.37% which was significantly higher than for pure sheep and pig manures and other ratios at the 0.05 level of significance.

4.1.5 Selected Manure Mix Ratios

Using, principal component 1 scores, the mix ratios of 1:1:3, 3:1:3 and 1:1:2 (cattle, pig and sheep manures) were top-ranked 1st, 2nd and 3rd, respectively. These were followed by 1:3:3, then, 1:1:1, 2:1:1, 3:1:1, 1:1:2, 3:1:1 and lastly 1:3:1, respectively. The variable that tends to have the largest score tend to be those that result in high parameter (Reris & Brooks, 2015). Hence, the three top-ranked mix ratios were selected to use in anaerobic digestion among the many to reduce the number of experiments due to time and resource limitations.

4.2 Effect of Various Mix Ratios, Total Solids and Organic Loading Rate on Biogas Production

4.2.1 Effect of Varying Mix Ratio on Biogas Production

Daily biogas production rates for the same mix ratios are represented in Table 4.2. Figure 4.1 shows the plot of biogas production rate against digestion period for various pure and various mix ratios of cattle, pig and sheep manures.

Table 4.2: Biogas yields from pure and mixtures of cattle, pig and sheep manures

Digestion period (days)	Gas yield (m^3/m^3d)					
	Pure manures			**Mix ratios**		
	Cattle (1:0:0)	Pig (0:1:0)	Sheep (0:0:1)	1:1:3	3:1:3	1:1:2
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.269	0.279	0.664
4	0.000	0.000	0.000	0.318	0.548	0.732
5	0.223	0.229	0.322	0.403	0.776	0.884
6	0.228	0.253	0.374	0.613	0.943	0.944
7	0.229	0.291	0.401	0.636	1.042	1.032
8	0.231	0.338	0.482	0.667	1.296	1.000
9	0.252	0.397	0.523	0.900	1.300	1.645
10	0.281	0.421	0.592	0.936	1.568	1.741
11	0.348	0.495	0.642	0.989	1.589	1.996
12	0.367	0.533	0.688	1.000	1.632	2.000
13	0.348	0.588	0.734	1.042	1.796	2.143
14	0.467	0.631	0.790	1.069	1.830	2.199
15	0.506	0.652	0.932	1.103	1.832	2.664
16	0.522	0.664	0.955	1.113	1.853	2.741
17	0.551	0.667	0.959	1.119	1.864	2.798
18	0.559	0.669	0.960	1.121	1.901	2.826
19	0.560	0.701	0.963	1.129	1.956	2.803
20	0.600	0.702	0.966	1.203	1.983	2.891
Total	6.274	8.231	11.283	15.630	25.990	34.136
Mean	0.314^{d}	0.412^{cd}	0.564^{cd}	0.782^{c}	1.300^{b}	1.707^{a}

Means followed by the same letter(s), (a, b, c, d), are not significantly different at α = 0.05, LSD = 0.332

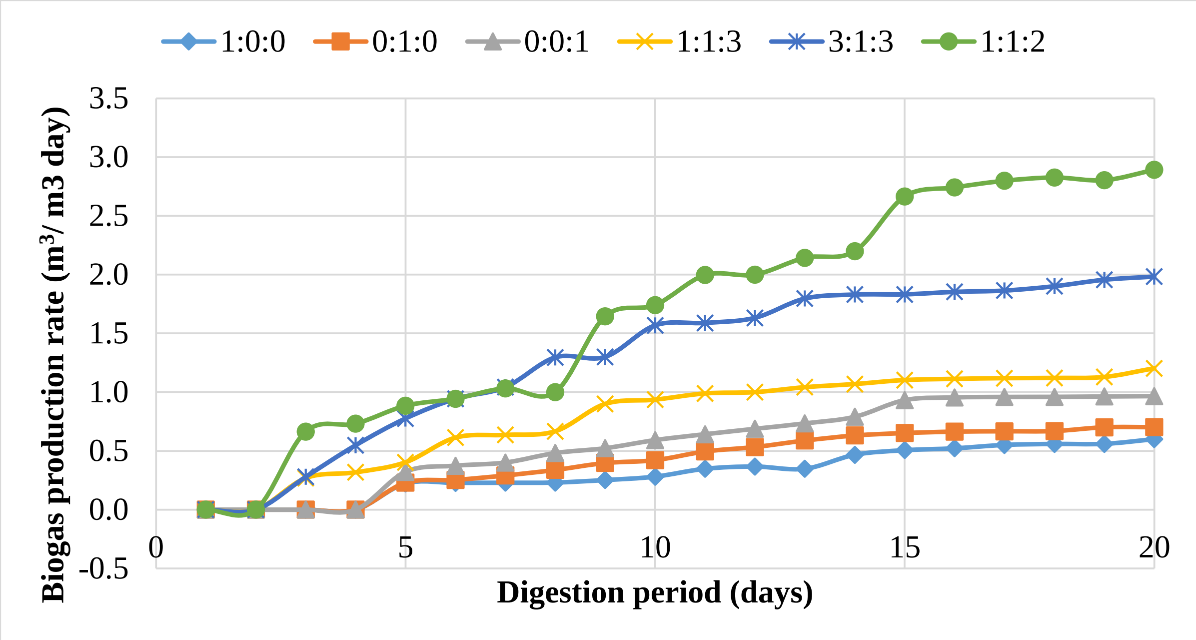

Figure 4.1: Biogas production trends of the various mix ratios at a constant feeding rate of 3kg VS/m^3day at 35±1^0C temperature and 8% TS

The graph shows the three phases: lag phase, exponential phase and stationary phase. The lag phase runs for 3 days for the mix ratios and 4 days for the pure manures. During this stage gas produced was not burning and this could be due to high VFAs production, decrease in pH value and lack of methanogens during the early days of digestion as explained by Jha et al. (2012).

The exponential phase followed to 14 days for the pure manures and to 15 for the mix ratios. During this stage, the gas produced was burning and this could be as a result methanogenesis process taking place producing biogas with methane content above 50% (Karki, 2009). Lastly, a steady phase follows to the 20^{th} day. The steadiness in biogas production could be due to the that the rate of organic degradation equals the rate of microbial growth throughout the stage. Figure 4.2 presents average biogas production.

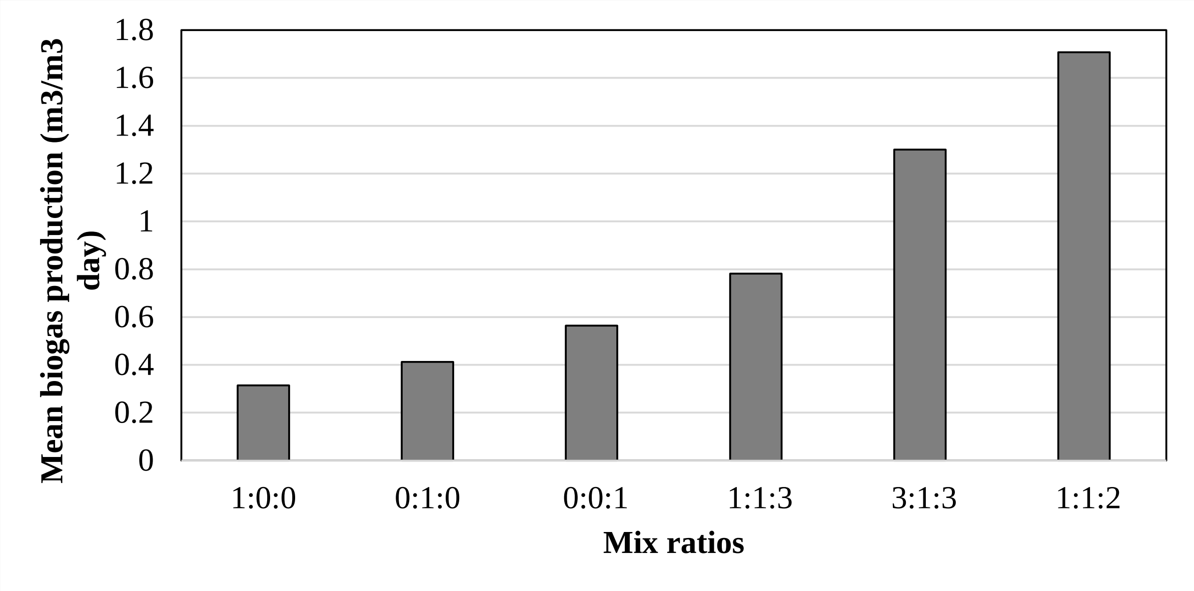

Figure 4. 2: Average biogas production for the mix ratios

The mean biogas yield for the three pure cattle, pigs and manures were 0.314, 0.412 and 0.564 respectively, which falls within the reported range by FAO (1997) including 0.20-0.35, 0.30-0.61 and 0.40-0.50m^3 /m^3 day, respectively.

As can be seen from the figure mix ratio 1:1:2 was leading with the mean biogas production rate of 1.707 m^3/m^3day, followed by 3:1:3 with 1.300 m^3/m^3day, 1:1:3 followed with 0.782 m^3/m^3day, sheep manure alone (0:0:1) followed with 0.564 m^3/m^3day, then pig manure with 0.412 m^3/m^3day and lastly 1:0:0 (cattle manure alone) with 0.314 m^3/m^3day. Mixing the three manures shows an improvement in biogas production rate compared to that of pure manures and these agree with what was reported by Sharom et al. (2004) and Battistoni et al. (2010) that co-digestion is better than mono-digestion.

Also, the biogas yield for the co-digestion of the three manures shows an improvement as it ranges from 0.782 - 1.707m^3 /m^3day compared to 0.31-0.48m^3 /m^3day for co-digestion of cattle dung and sheep (Ngunjiri et al., 2015) and up to 0.35 m^3 /m^3day for cattle dung and pig manure (FAO, 997). Such enhancement may be ascribed to more available fermentable compounds (sugars and acids) and also advancement of the activity of microbes, especially the activity of methanogens brought by the co-digestion (Kangle et al., 2012; Li et al., 2020).

4.2.2 Effect of Varying Total Solid on Biogas Production

The daily biogas production rates for the various total solids are shown in Table 4.3.

Table 4.3: Gas yields for various total solids

Digestion period (days)	**Gas yield (m^3 /m^3d)**			
	Total solids (%)			
	6	8	10	12
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.120	0.269	0.000	0.000
4	0.195	0.318	0.000	0.000
5	0.257	0.403	0.103	0.000
6	0.364	0.613	0.182	0.125
7	0.573	0.636	0.301	0.177
8	0.604	0.667	0.384	0.256
9	0.683	0.900	0.437	0.284
10	0.781	0.936	0.586	0.332
11	0.816	0.989	0.694	0.374
12	0.854	1.000	0.769	0.432
13	0.896	1.042	0.799	0.444
14	0.901	1.069	0.802	0.460
15	0.950	1.103	0.831	0.489
16	0.954	1.113	0.852	0.513
17	0.956	1.119	0.858	0.526
18	0.961	1.121	0.862	0.530
19	1.009	1.129	0.878	0.539
20	1.013	1.203	0.883	0.544
Total	12.888	15.630	10.221	6.025
Mean	0.644^{ab}	0.782^{a}	0.511^{b}	0.301^{bc}

Means followed by the same letter(s), (a, b, c, d), are not significantly different at $\alpha = 0.05$, LSD = 0.212

Results in Table4.3 shows that TS 8% was leading with the mean biogas production rate of 0.644, followed by 6% with 0.782, then 10% with 0.511 and lastly 12 with 0.301 m^3 /m^3day. Figures 4.3 and 4.4 show the results of biogas production rate and mean biogas production rate while digesting 1:1:3 cattle to pig to sheep manure mixtures at 35±1°C being fed at 3kg VS/m^{3}day at varying total solids (6%, 8%, 10% and 12%).

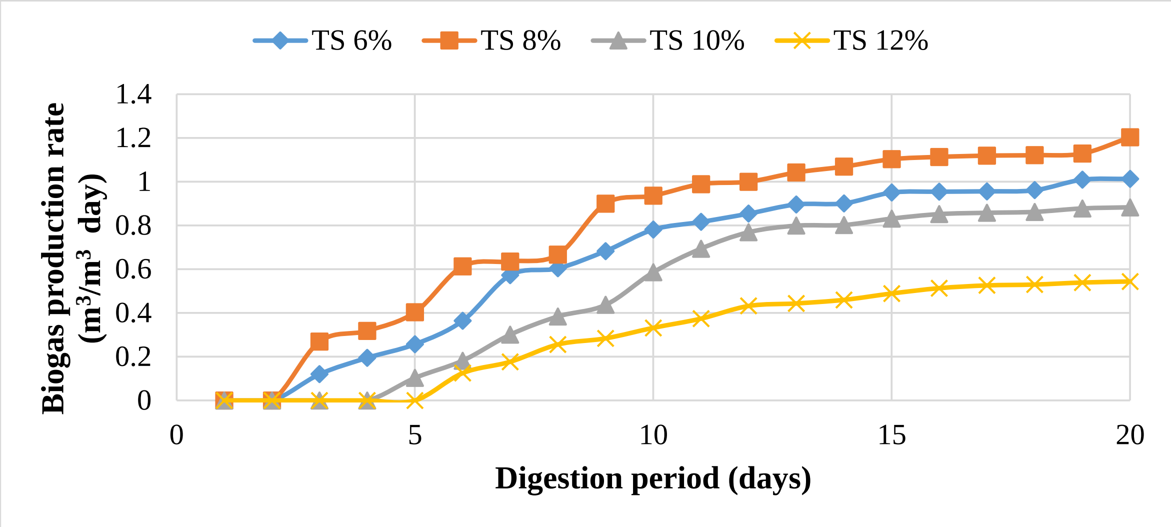

Figure 4.3: Biogas production rates of various total solids at 35±1^{0}C temperature, 3kg VS/m^{3}day OLR and a mix ratio of 1:1:3

Substrate degradation takes place between 2nd for the total solids 6 and 8%, 4th and 5th days for 10 and 12% respectively. Followed by an exponential rise in biogas production to the 15th day for 6, 8, and 10% and day 12 for 12%. A steady phase then followed to the 20th day.

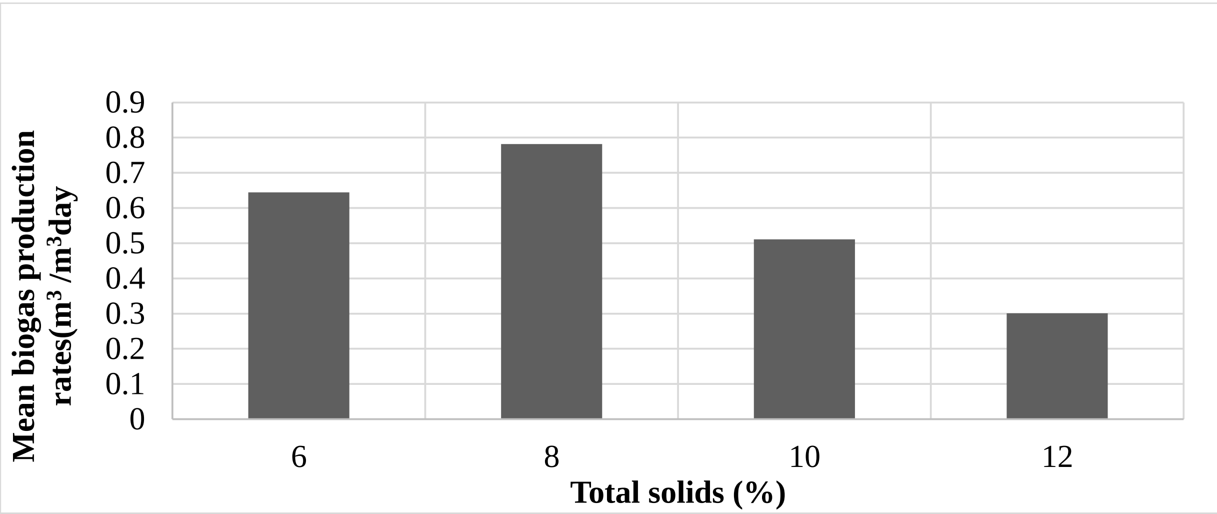

Figure 4.4: Average biogas production for the various total solids

As evident in Figure 4.4, there was a gradual increase in gas yield with an increase in TS from 6 to 8% by 21.43% followed by a 61.48% decrease as total solids increased from 8% to 12%. The drop in biogas yield observed in this research work could be a result of too much total solids leading to clogging of the system which reduces the level of microbial activity (Orhorhoro, 2017). From the results biogas produced is a power function of the total solids content and production increases with an increase in % TS until an optimum point. These results are in agreement with what Igoni et al. (2008) and Yavini et al. (2014) reported.

Total solids significantly affected biogas production rate at 5% level of confidence (LSD=0.212). The rate of biogas production for 6 and 8%, 6 and 10%, 10 and 12 % were not significantly different from each other but 8 and 10% and 8 and 12 were significantly different from each other. This implies that TS 6 and 8% with mean biogas production rate of 0.644 and 0.782m^3 /m^3day is recommended.

4.2.3 Effect of Varying Organic Loading Rate on Biogas Yield

Table 4.4 presents the gas yields for the 1, 2, 3 and 4 kg VS/m^3day organic loading rates with the time of digestion using 1:1:3 cattle, pig and sheep mix ratio, 8% TS and 35±1℃ temperature.

Table 4.4: Gas yields for various OLR

Digestion period (days)	Gas yield (m^3/m^3d) Organic loading rate (kg VS/m^3day)			
	1	2	3	4
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.325	0.325	0.318	0.325
5	0.403	0.403	0.403	0.403
6	0.613	0.613	0.613	0.613
7	0.664	0.664	0.664	0.664
8	0.667	0.667	0.667	0.6667
9	0.700	0.801	0.900	1.261
10	0.710	0.811	0.936	1.055
11	0.719	0.829	0.989	0.683
12	0.727	0.837	1.000	0.539
13	0.754	0.857	1.042	0.403
14	0.770	0.870	1.069	0.199
15	0.792	0.906	1.103	0.180
16	0.822	0.947	1.113	0.173
17	0.826	0.960	1.119	0.171
18	0.827	0.973	1.121	0.144
19	0.829	0.974	1.129	0.119
20	0.831	0.973	1.203	0.115
Cumulative	11.980	13.410	15.390	7.714
Mean	0.599^{ab}	0.671^{a}	0.770^{a}	0.386^{ab}

Means followed by the same letter(s), (a, b, c, d), are not significantly different at $\alpha = 0.05$, LSD = 0.242

From Table 4.4 biogas yield averages for 1, 2 and 3 kg VS/m^3day OLR obtained were 0.599, 0.671 and 0.769 m^3/m^3 day respectively. Highest production rate was achieved at 3 kg VS/m^3day which is within the reported optimum range of 2.5-3.5 kg VS/m^3 day (Kinyua, 2013).

OLR significantly affected the biogas production rate at 5% level of confidence (LSD=0.242). The rate of biogas production for 1and 2, 1 and 3, 1 and 4 and 2 and 3kg/m^{3}day were not significantly different from each other but 3 and 4 and 2 and 4kg/m^{3}day were significantly different from each other. Hence, OLR 2 and 3kg VS/m^{3}day with the mean biogas production rate of 0.671 and 0.768m^3/m^{3}day respectively are recommended. Figure 4.6 shows the plot of an average biogas production rate for the various organic loading rates.

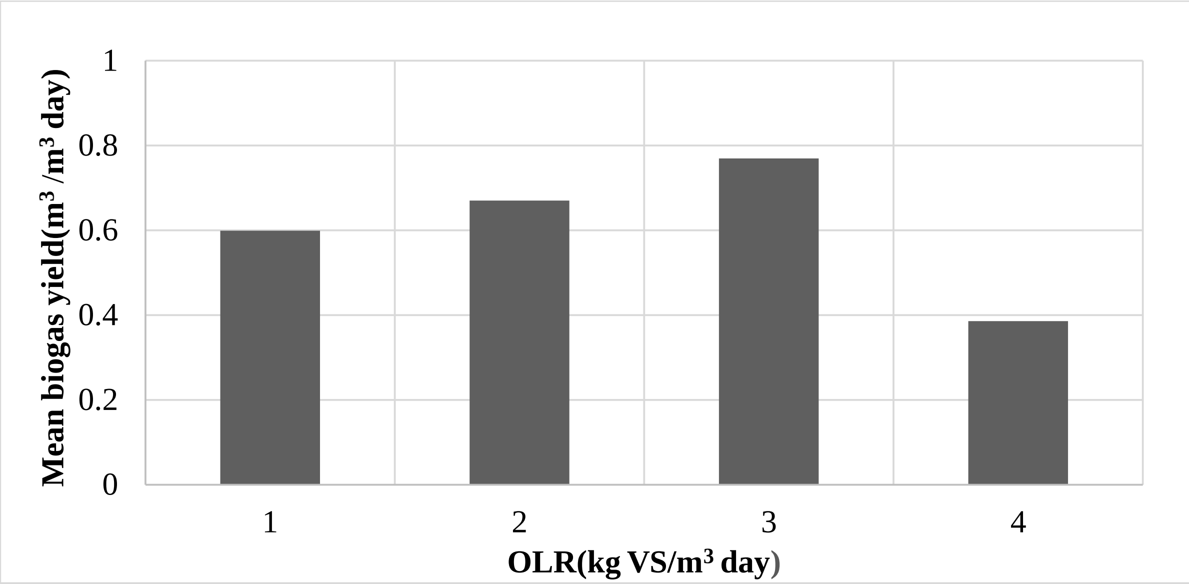

Figure 4. 5: Average biogas production for the various OLR

Figure 4.5 shows that biogas yield increases with an increase in OLR from 1 to 3kg/m^{3}day. This observation agrees with the report given by Sunny and Joseph (2018) on their review that biogas production increases with an increase in feeding rate due to an increase in metabolic activity of bacteria. Further, increasing to 4kg/m^{3}day led to a decrease in biogas yield and this agreed with the findings of Babaee and Shayegan (2011) and Chen et al. (2014) that continuous increase in OLR caused a decrease in biogas production. The decrease in production could be due to digester overfeeding which results in implications such as bacteria wash out and volatile fatty acids accumulations (Sarker et al., 2019).

4.3 Optimization of Total Solids, Feeding Rate and Mix Ratios on Biogas Production

The experimental average biogas production rate as influenced by the total solids, organic loading rate and mix ratios and their Taguchi corresponding signal to noise ratios are presented in Table 4.5.

Table 4.5: Optimization results

Experiment No.	Total solids (%)	Feeding rate (kg VS/m^3 day)	Mix ratios	Biogas production rates (m^3 /m^{3}d)	
				Mean	S/N ratio
1	6	2	1:1:3	0.549	-9.328
2	6	3	1:1:2	1.195	-1.997
3	6	4	3:1:3	0.734	-5.333
4	8	2	1:1:2	1.524	2.591
5	8	3	3:1:3	1.300	-0.892
6	8	4	1:1:3	0.352	-13.130
7	10	2	3:1:3	0.745	-5.606
8	10	3	1:1:3	0.511	-9.175
9	10	4	1:1:2	0.434	-9.250

The use of a Taguchi method in optimizing biogas production rate involved 27 runs compared to the factorial method which involved 81 runs. This supported the conclusions of Youssef et al. (1994) and Ballal et al. (2012) that using a Taguchi method involved a smaller number of analytical investigations than a factorial optimization method.

Table 4.6 presents the average signal to noise ratios for the factors' levels. Response graphs for the biogas production rate performance measures are presented in appendix 5, Figure A5.1.

Table 4.6: Signal to Noise ratios and the corresponding ranges and ranks

Factors	Mean S/N Ratios				
	Level 1	Level 2	Level 3	Range	Rank
Total solids (%)	-5.552 (6)	-3.811 (8)	-8.010 (10)	4.200	3
Organic loading rates (kg VS/m^3 day)	-4.114 (2)	-4.022 (3)	-9.238 (4)	5.216	2
Mix ratios	-10.544 (1:1:3)	-2.885 (1:1:2)	-3.944 (3:1:3)	7.659	1

NB: The higher the S/N the better

The greatest influence on biogas production rate was mix ratios as it is ranked number one in Table 4.6, followed by organic loading rates and total solids had the least effect. Using the higher the S/N the better, optimal values were achieved with the second level of the mix ratios (1:1:2), the second level of total solid (8%) and the second level of the organic loading rate (3kg VS/m^3day). A Confirmation experiment was carried out at the selected optimal setting and it produces the greatest mean biogas production rate of 1.732m^3 /m^3 day.

CHAPTER FIVE

CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

Total solids, C/N ratios, pH and volatile solids were used to characterize various mix ratios of cattle manure, pig and sheep manures. Performance evaluation was also carried out to quantify the effects of mix ratios, total solids and organic loading rate on biogas production rate. Three mix ratios, total solids and organic loading rate were investigated to identify the optimum combination of the factors.

Based on the performance evaluation and the results obtained, the following conclusions can be drawn:

1. Upon mixing cattle manure, pig manure and sheep manure at various mix ratios the total solids content, Carbon to nitrogen ratio, pH and volatile solids content varies from 22.280% to 26.750%, 18.760 to 25.050, 7.133 to 7.567 and 85.940% to 82.590% respectively.
2. Mix ratio 1:1:3, 3:1:3 and 1:1:2 of cattle to pig to sheep manures resulted in an increase in biogas production rate compared to pure manures. Increasing loading rate from 1-3kg VS/m^3 resulted in a 29% increase in biogas production rate and further increase from 3 to 4 kg VS/m^3 day decreases biogas production rate by 50%. There was a 21.43% increase in biogas yield as TS increases from 6 to 8% followed by a 61.48% decrease from 8% to 12%.
3. Optimal biogas production rate performance of 1.732m^3 /m^3 day was achieved using a 1:1:2 mix ratio, 8% TS and a 3kg VS/m^3 day.

5.2 Recommendations

5.2.1 Recommendations for Biogas Industry

The following recommendations were made:

1. This research considered mixing of only cattle manure, pig manure and sheep manure. It did not consider using other wastes or mixtures. It is thus recommended that further research could be done to study biogas production of cattle manure mixed with other substrates such as chicken wastes, kitchen waste, tea waste, maize cobs and the slaughter house waste.
2. A mix ratio of 1:1:2, total solid 6 and 8% and the 2 and 3kg VS/m^3day organic loading rate are recommended.

5.2.2 Recommendations for Further Research

1. Research should be carried out on the effects of mixing frequency, feeding frequency, recirculation and temperature on biogas production rate.
2. Biogas production rate should be optimized using other optimization methods such as response surface methodology (RSM) and artificial neural networks (ANN) to confirm the optimal settings.

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APPENDICES

Appendix 1: Characterization of various mix ratios

A1.1 A laboratory analysis of biophysical characteristics of the different mix ratios of cattle manure, pig manure and sheep manure

a) **Total solid (TS)**

$$\%TS = \frac{W_1 - W_2}{W_3 - W_2} \times 100\% \qquad \text{(A.1)}$$

Where,

%TS = Percentage total solid

W_1 = Weight of dried crucible + dried residue

W_2 = Weight of crucible

W_3 = Weight of wet sample (substrate) + crucible

b) **Organic carbon content (Walkey black method)**

$$C = \frac{(B - T) \times V \times 0.3}{WB} \qquad \text{(A.2)}$$

Where,

B = blank titre

V = volume of potassium dichromate added

0.3=concentration of 1ml potassium dichromate seven added=0.003*100

W=weight of the sample=0.5g

c) **Determination of Nitrogen content (Kjedhal method)**

$$N = \frac{(a - b) * 100 * 100 * 0.014}{wv} \qquad \text{(A.3)}$$

Where,

0.014=Concentration/Molarity of Nitrogen in 1 litre

100=Dilution factor

100=Conversion factor into %

a=volume titre

b=blank titre

v=mls of aliquot

A1. 2: Principal component analysis Matlab script

a) Principal component coefficients, scores and latents

```
%A represent measurements taken of the different mix ratio
>> A= [TS C/N Ph VS];
%determination of the size of the data
>> [n m];
% calculation of mean
>>A mean = mean (A);
% calculation of standard deviation
>>A std = std (A)
% standardization which means subtracting the sample mean from each observation then dividing by standard deviation
>>B =Z score (A);
% determining the coefficients, respective latent and scores
%`Coffecient` principal component vectors
% `latent` eigenvalues of covariance matrix of A arranged in order
% `score` projection of the original data onto the principal component axis
>> [COEFF SCORE LATENT] = princomp (B)
```

b) Projection of the original data in the space of the three principal components

```
X= [ Ts C/N pH VS];
 X = X(all(~isnan(X),2),:);
 [coefs,score] = pca(zscore(X));
 vlabs = {‘Ts,CN,pH,VS '};
 biplot (coefs (:,1:3), 'scores',score(:,1:3), 'varlabels',vlabs)
```

c) Projection of the original data in the space of the first two principal components

```
X= [ TS C/N pH VS];
 X = X(all(~isnan(X),2),:);
 [coefs,score] = pca(zscore(X));
 vlabs = { Ts,CN,pH,VS '};
 biplot (coefs (:,1:2), 'scores',score(:,1:2), 'varlabels',vlabs)
```

d) Plotting of the principal components

```
X= [TS C/N Ph VS];
[coefs,latent,explained]=pcacov(X);r
Figure ();
pareto(explained);
xlabel ('Principal component');
ylabel ('Variance Explained (%)')
```

e) Scree plottingD

```
A= [TS C/N Ph VS];
Amean=mean(A);
Astd=std(A);
B=zscore(A);
[Coefs, Score, latent] = pca(B);
explained=cumsum(latent). /sum(latent);
scree(explained);
xlabel ('principal component');
ylabel ('Variance Explained (%)')
```

A1. 3 Determination of the organic loading rate

Volume of digester, Vd = $0.15m^3$

Volume to be fed= 80% of Vd = $0.12\ m^3$

$$Vd = daily\ slurry\ input * retention\ time$$

$$daily\ slurry\ input = \frac{Vd}{retention\ time}$$

$$daily\ slurry\ input = \frac{0.12m^3}{17days}$$

$$= 0.0070588m^3/day$$

Density of slurry= $1000kg/m^3$

$$Loading\ rate(LR) = \frac{1000kg}{m^3} * 0.0070588m^3/day$$

$$= 7kg\ /\ day$$

$$OLR(Kg\ VS/M^3day) = \frac{LR \times VS}{V}$$

Where,

OLR= Organic loading rate

LR= Loading rate

VS= Volatile solid content

V= Volume of the digester

A1. 4 Determination of the amount of water to be added to feedstock

For example, to prepare an influent having 8% TS; the following calculations will be done

$$The\ average\ TS\ of\ substrate\ = x\%$$

$$\Rightarrow 1\ kg\ of\ substrate\ contains\ \left(\frac{1 \times x}{100}\right) = 0.1x\ kg\ of\ TS$$

$$But\ for\ a\ 8\%\ TS\ influent,$$

$$\Rightarrow 8kg\ of\ TS\ are\ contained\ in\ 100\ kg\ of\ influent\ \therefore x\ kg\ are\ contained\ in\ \left(\frac{x \times 100}{7}\right)$$

$$= 14.29x\ kg\ of\ influent$$

$$The\ amount\ of\ water\ to\ be\ added\ in\ 1kg\ TS\ of\ feedstock = 14.29x\ kg\ - 1$$

$$the\ ratio\ of\ feedstock: water = 1: (14.29x - 1$$

Appendix 2: Biodigester plate

A2.1 Plates

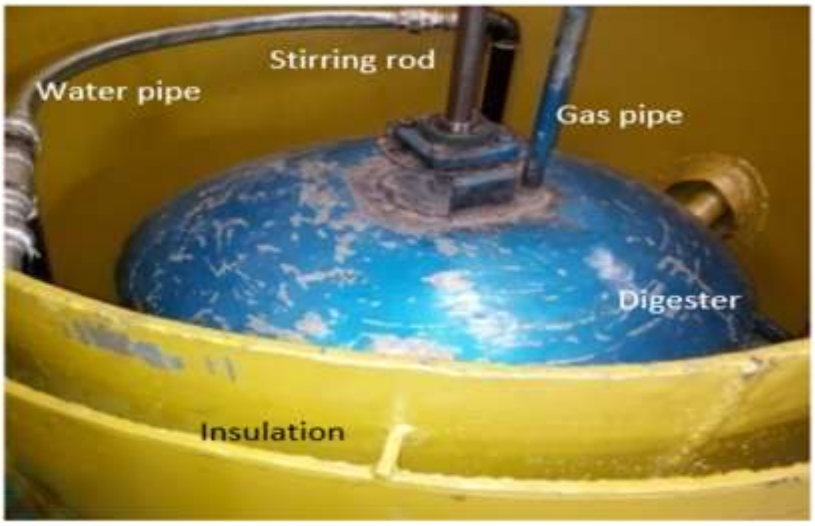

Plate A2.1: Bio-reactor

Plate A2.2: Expansion chamber

Plate A2.3: Water tank with immersion heaters

A2.2 Schematic diagram of a lab bio- digester

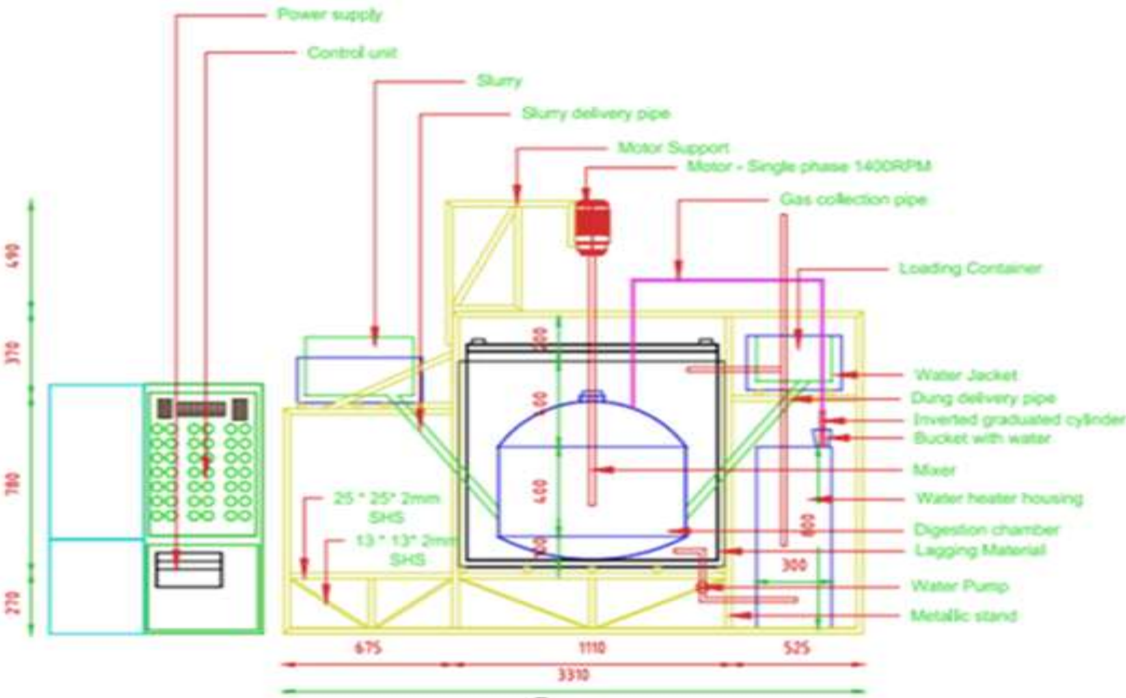

Figure A2.1: Cross section of a lab digester

Appendix 3: Projection of data and original variables in the principal component axis and scree plotting

Table A3.1: Principal components' coefficients

Characteristic	Principal component 1	Principal component 2	Principal component 3	Principal component 4
TS	0.430	-0.597	-0.558	-0.384
C/N	0.593	0.291	-0.322	0.679
Ph	0.613	-0.210	0.757	-0.087
VS	0.297	0.717	-0.113	-0.620

Table A3.2:Principal components' scores

Mix ratio	PC_1 scores	PC_2 scores	PC_3 scores	PC_4 scores
1:1:1	-0.006	-0.001	-0.002	0.004
3:1:1	-0.259	2.182	-0.010	-0.001
1:3:1	-2.287	-1.260	-0.003	-0.001
1:1:3	2.539	-0.919	-0.002	-0.003
2:1:1	-0.147	1.361	0.013	0.000
1:2:1	-1.440	-0.781	-0.011	-0.000
1:1:2	1.580	-0.572	-0.014	0.001
1:3:3	0.191	-1.566	0.018	-0.0001
3:3:1	-1.810	0.653	0.005	-0.001
3:1:3	1.638	0.902	0.007	0.000

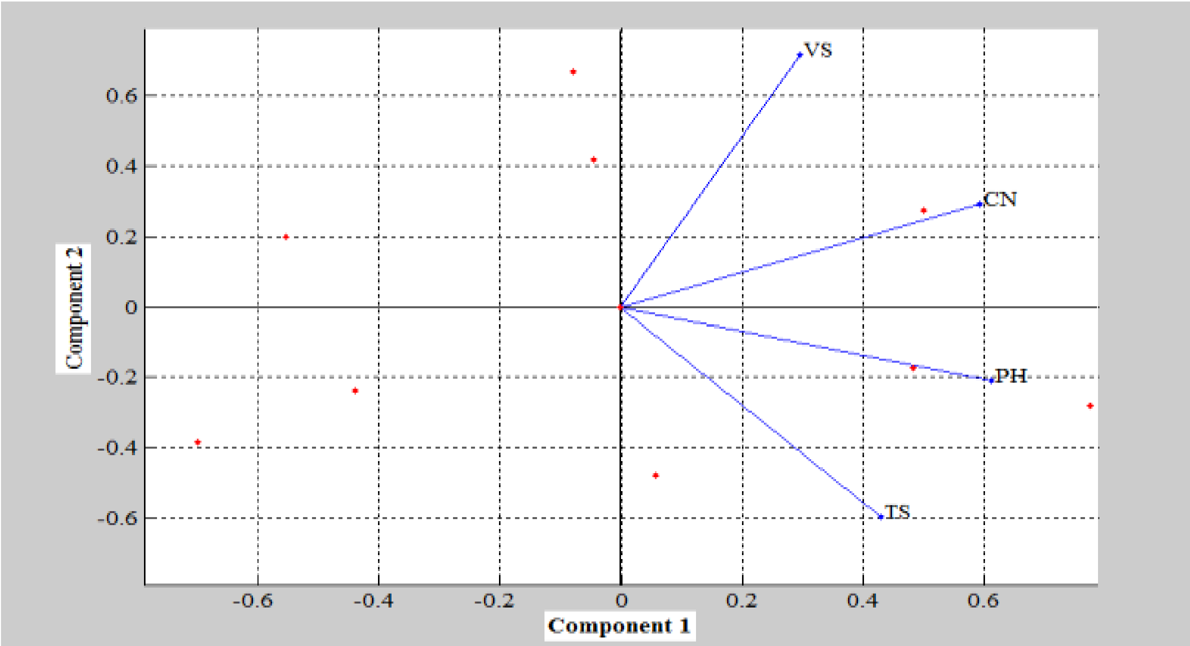

Figure A3.1: Data and original variables in the space of first two principal components

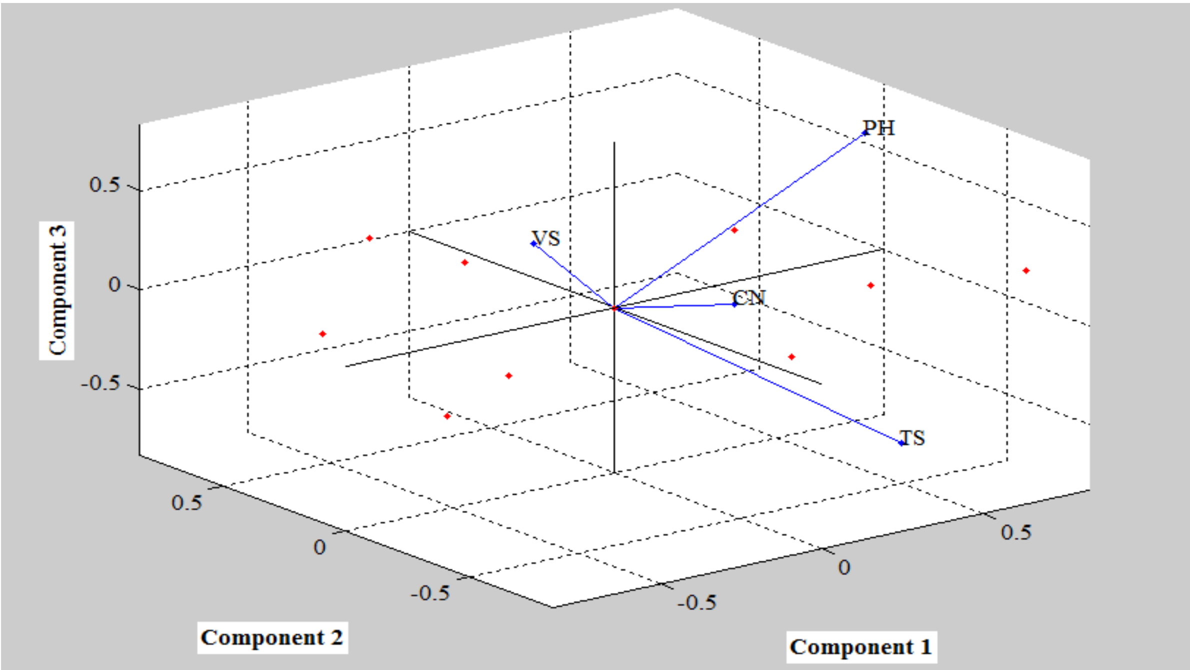

Figure A3.2: Data and original variables in the space of first three principal components

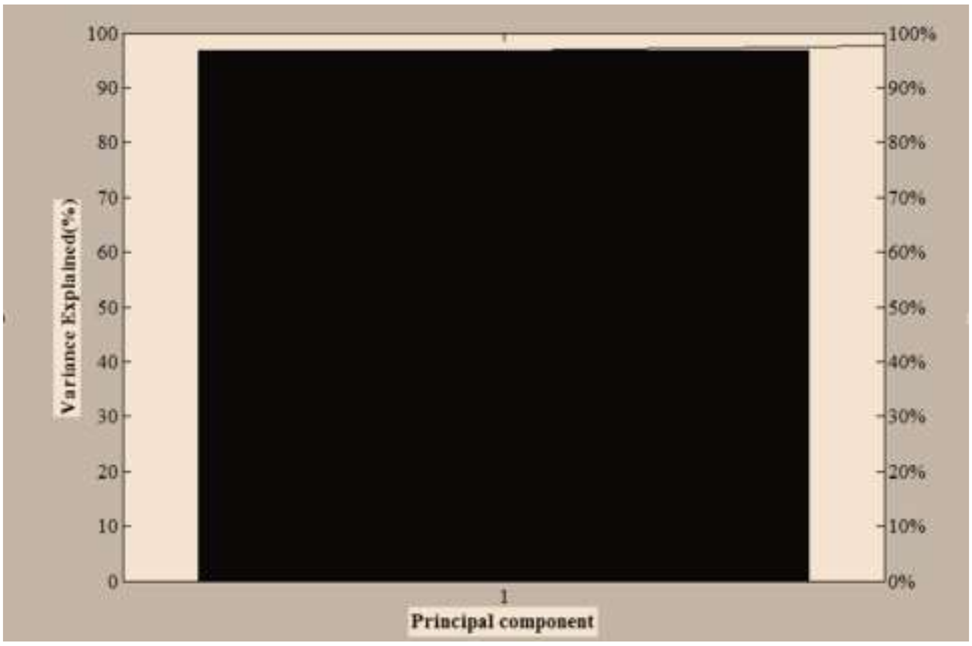

Figure A3.3: Scree plot

Appendix 4: ANOVA for performance indicators

Table A4.1: ANOVA for the gas yields of various mix ratios

Source of variation (SoV)	Degree of freedom (DF)	Sum of squares (SS)	Mean sum of squares (MS)	$F_{Calculated}$= MST/MSE	$F_{Critical}$ (5%)
Total	119	62.120			
Treatment	5	30.047	6.009		
Error	114	32.073	0.281	21.359	2.296

*Significant

Table A4.2: ANOVA for the gas yields of various total solids

Source of variation (SoV)	Degree of freedom (DF)	Sum of squares (SS)	Mean sum of squares (MS)	$F_{Calculated}$= MST/MSE	$F_{Critical}$ (5%)
Total	79	11.121			
Treatment	3	2.511	0.837		
Error	76	8.610	0.113	7.387	2.730

*Significant

Table A4.3: ANOVA for the gas yields of various OLR

Source of variation (SoV)	Degree of freedom (DF)	Sum of squares (SS)	Mean sum of squares (MS)	$F_{Calculated}$= MST/MSE	$F_{Critical}$ (5%)
Total	79	12.790			
Treatment	3	1.598	0.533		
Error	76	11.192	0.147	3.617	2.730

*Significant

Appendix 5: Optimization experiment results

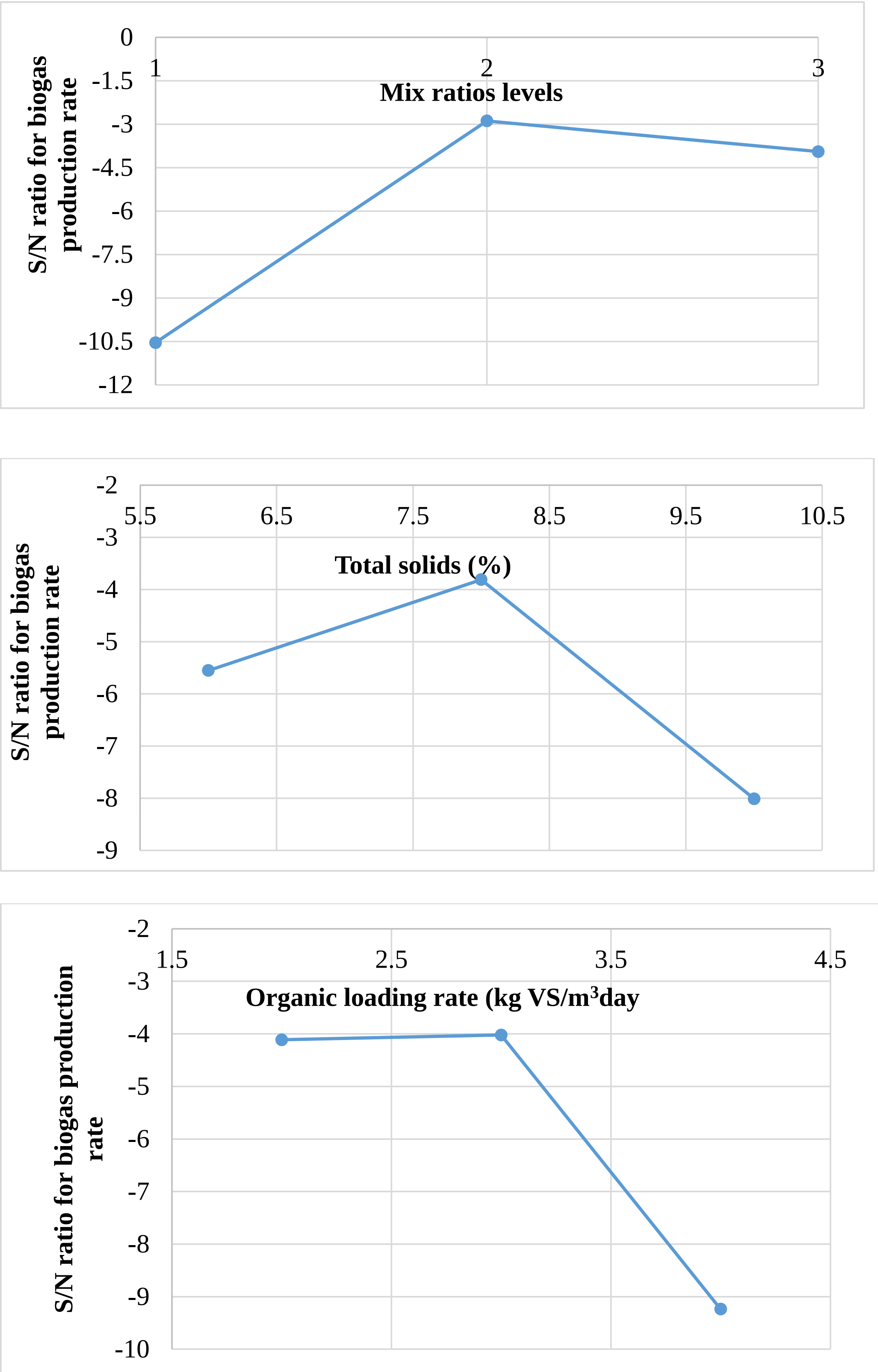

Figure A5.1: Response graphs for biogas production rate performance measures

Appendix 6: Plates

Plate A6.1: Feedstock samples for characterization

Plate A6.2: Feedstock samples for anaerobic digestion

Plate A6.3: Substrate preparation

Plate A6.4: Weighing of substrates

Appendix 7: NACOSTI Authorization Certificate

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Appendix 8: Relevant Publications based on this Work

Characterization and Ranking of Various Mix Ratios of Cow, Pig and Sheep Manure

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Authors' contributions

This work was carried out in collaboration among all authors. Author SCM designed the study, managed the literature searches, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors DMN and BOO managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

This work determined the characteristics of various mix ratios of the cow to pig to sheep manures and ranked them with help of principal component analysis (PCA). Ten mix ratios (by mass) namely 1:1:1, 3:1:1, 1:3:1,1:1:2, 2:1:1, 1:2:1, 1:1:2, 1:3:3, 3:3:1, 3:1:3 of cow, pig and sheep manures respectively were selected. Laboratory analysis was done to determine the total solid (TS) content, carbon to nitrogen ratio, pH, and volatile solid (VS) content using standard procedures. The results obtained (except that of pure feedstocks) were subjected to principal component analysis to determine the principal component scores for the mix ratios to enable ranking. The total solids content of pure cow, pig, and sheep manure were found to be 19.18%, 23.50%, and 30.35% respectively. Corresponding carbon to nitrogen ratios values were 23.68, 13.27 and 29.00, pH values were 6.50, 7.90 and 7.00 and volatile content were 88.37%, 84.57% and 80.00%. Upon mixing the three manures at various mix ratios total solid content varies from 22.28% to 26.75%. Total solids content, carbon to nitrogen ratio, pH and volatile solids content varies from 22.28% to

OPTIMAL MIX RATIO, TOTAL SOLIDS AND ORGANIC LOADING RATES FOR ANAEROBIC DIGESTION

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ABSTRACT:

Biogas technology is a sustainable and valid alternative to fossil fuels. It reduces greenhouse gas (GHG) emissions and can enhance energy security. pH, temperature, retention time, particle size, volatile solid content, inoculums, mix ratios (MR), total solid (TS) and organic loading rate (OLR) are among the factors that influence biogas production. Some studies have been done to determine optimal values of these factors for various feedstocks. The aim of this work was to determine the dependency of mix ratios (MR), total solids (TS) and organic loading rate (OLR) and their corresponding optimal values during anaerobic co-digestion of cow dung (CD), pig (PM) and sheep manure (SM). Tests were done using a $0.15m^3$ fixed dome laboratory reactor under a constant temperature of 35±1°C, 20 days operation period and gas yield was measured using water displacement method. A mix ratio of 1:1:2 (CD: PG: SM) lead with yield rate of $1.707m^3/m^3$day followed by 3:1:3 with 1.300, then 1:1:3 with 0.782 and lastly 1:0:0 with $0.314m^3/m^3$day. These values were significantly different at α=0.05 (LSD=0.392). There was an increase in biogas yield as TS increases from 6 to 8% followed by a decrease from 8% to 12%. Mean gas yields for 6, 8, 10 and 12% TS were 0.782, 0.644, 0.511 and $0.301m^3/m^3$day respectively. TS 6 and 8%, 6 and 10%, 10 and 12 % were not significantly different from at α=0.05 but for 8 and 10% and 8 and 12% were significantly different (LSD=0.212). The biogas production rate for 1, 2, 3 and $4kgVS/m^3$day OLR were 0.599, 0.671, 0.769 and $0.386m^3/m^3$day respectively. Mean yields for 1 and 2, 1 and 3, 1 and 4 and 2 and $3kgVS/m^3$day were not significantly different at α=5% but for 3 and 4, 2 and $4kg/m^3$day were significantly different (LSD=0.2417). It was then concluded that 1:1:3, 3:1:3 and 1:1:2 resulted in an increase in biogas production rate of 0.468, 0.986, and 1.393 respectively compared to pure cow dung. There was a 21.43% increase in biogas yield as TS increases from 6 to 8% followed by a 61.48% decrease from 8% to 12%. Increasing loading rate from 1-3kg VS/m^3 resulted in 29% increase in biogas production rate and further increase from 3 to 4 kg VS/m^3 day decreases biogas production rate by 50%. Mix ratio of 1:1:2, TS 6 and 8% and OLR 2 and $3kgVS/m^3$day were then recommended.

Keywords: Mix ratios, total solids, organic loading rate, biogas, co- digestion