Electricity and Gas Potential of Abattoir Waste

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ABSTRACT

Slaughterhouse operations generate huge volumes of organic wastes which include dung, fats, blood, animal trimmings, urine, and paunch contents. Slaughterhouse wastes should be carefully handled and processed because are a potential source of bacterial, prion, viral, and parasitic pathogens, that can infect humans and animals. Disposal methods include composting, rendering, anaerobic digestion (AD), alkaline hydrolysis (AH), incineration and incineration. Slaughterhouse waste especially that with high fat and protein of slaughterhouse is excellent substrate for anaerobic digestion processes that leads to both disposal, nutrient recycling, and in methane generation. Slaughterhouse waste can pollute air, soil, and water if disposed of untreated or poorly managed. This study demonstrates the potential of abattoir waste in the energy transition to renewable energy and low carbon electricity. The performance of operating slaughterhouse was used as a basis feasibility assessment. The composition of slaughterhouse waste was presented, and production output estimated under current and optimal conditions. Slaughterhouses can be meet their own internal energy use and export excess as biogas, biomethane or electricity. This will earn extra revenue, mitigate against greenhouse gas emissions by displacing fossil fuel sources and solve the challenge of waste treatment and disposal.

Key Words

Anaerobic digestion; Slaughterhouse; Slaughterhouse waste; biogas production, biogas from slaughterhouse waste.

1.0. INTRODUCTION

Abattoirs or slaughterhouses produce significant quantities of biodegradable organic wastes such mainly in form of blood, fat, feaces, fat, blood, animal trimmings, paunch contents and urine. Slaughterhouse waste can be disposal of by composting, alkaline hydrolysis (AH), rendering, anaerobic digestion (AD), rendering, incineration and burning. By composting slaughterhouse waste nutrients are recycled back soil. The high fat Slaughterhouse waste with high fat and protein content is excellent substrate for anaerobic digestion hence methane production. Alkaline hydration has ability to inactivate almost all known microorganism (Franke-Whittle & Insam, 2013; Kabeyi, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022). These wastes have potential to pollute the environment like air, water, and soil, if left untreated or is poorly handled(Selormey et al., 2021). The most used method of slaughterhouse waste disposal is landfilling which pollutes the environment in form of greenhouse gas emissions, pungent or bad smell/odor and leachate management. For high waste loads and stringent environmental regulations, anaerobic digestion is an appropriate method for slaughterhouse treatment(Selormey et al., 2021). Slaughterhouse waste is energy rich having high concentrations of carbohydrates, mainly in the like lactose, proteins and lipids(Selormey et al., 2021). Main inhibitors of slaughterhouse to biogas production are high concentrations of ammonia, long chain fatty acids and hydrogen sulphide as they inhibit methanogenic activities as they are often digester upsets(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021a, 2021b; Selormey et al., 2021). The general methane potential of slaughterhouse waste streams generally ranges from 49.5 to 650.9 $mLCH_4\ gVS^{-1}$ while energy potential can meet the entire needs of the slaughterhouse from mixed waste stream and still have excess for commercial use like export of electricity or sale of biogas and biomethane(Kabeyi & Olenwaraju, 2020; Kabeyi & Oludolapo, 2020c, 2020f; Ware & Power, 2016).

There is a global determination to fight environmental degradation, guarantee food security and stabilize environment to realize sustainable development by use of green sources of energy (Kabeyi & Oludolapo, 2020b, 2021). Slaughterhouses give rise to significant quantities of solid waste which should be treated to avoid environmental pollution. Conversion to biogas is a potential waste disposal strategy for slaughterhouse waste(Kabeyi, 2019; Moses Jeremiah B. Kabeyi & O. A. Olanrewaju, 2021; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022). This study targeted Nyongara slaughterhouse based in Dagoretti, 26km away from Nairobi, as shown in figure 1 below. It is one of the many slaughterhouses in Nairobi and its surrounding. It is one of the major meat supplies in both Nairobi and Kiambu counties. On average, 200 cows and 400 sheep are slaughtered every day. Due to the handling of many animals daily, the slaughterhouse faced numerous challenges since its inception. One of the key challenges being high electricity bills of Ksh 30,000 monthly (Kabeyi & Oludolapo, 2020c). Electricity was used for lighting up the slaughterhouse, cooking food for the slaughterhouse workers, boiling water for use in the abattoir, and for washing the workers' blood-stained coats. The chemical properties of slaughterhouse wastes are similar to municipal sewage; however, the former is highly concentrated wastewater with about 45% soluble solids and 55% suspended organic composition (Sims et al., 2003). Blood has a very high COD of around 375,000 mg/L and is one of the major dissolved pollutants in slaughterhouse wastewater (Sims et al., 2003). In most of the developing countries, there is no organized strategy for disposal of solid waste as well as liquid wastes generated in abattoirs. The solid slaughterhouse waste is collected and dumped in open areas while the liquid waste is channeled to municipal sewage system or surface water bodies, thus endangering public health as well as terrestrial and aquatic life(M. Kabeyi & O. Olanrewaju, 2022; M. J. B. Kabeyi & A. O. Olanrewaju, 2022; Kabeyi & Oludolapo, 2020a). Wastewater from slaughterhouses is known to cause an increase in the BOD, COD, total solids, pH, temperature, and turbidity, and may even cause deoxygenation of water bodies. The study at Nyongara slaughterhouse showed that solid waste amounts to 16,000kg alongside 40m^3 of liquid waste daily. Kshs 100,000 was spent monthly on solid waste disposal(Kabeyi & Oludolapo, 2020e; USDA, 2019). The liquid waste is channeled untreated to Kabuthi River which drains into the Nairobi River, causing a hazardous level of pollution as shown in figure 2. Slaughterhouses in Kenya are required to follow National Environment Management Authority (NEMA) laws of waste disposal to curb surface disposal that contaminates water bodies, air, and soil. The overwhelming stench of solid waste and effluent was blown over a radius of almost two kilometers away from the slaughterhouse (Kabeyi & Oludolapo, 2020c).

The purpose of this study was to establish the performance of the existing biogas produced by the biogas facilities utilizing slaughterhouse waste and energy biogas potential of individual and combined waste streams. Important parameters for bio digestion or slaughterhouse waste are investigated are the design specification of the plant, its gas production in terms of quantity and quality and environmental impact of the project and the slaughterhouse (AgSTAR, 2020; Tanigawa, 2017). This research seeks to determine the biogas and energy potential of slaughterhouse organic waste streams and establish recoverable energy potential by exploitation of anaerobic digestion as an alternative waste treatment method for biodegradable slaughterhouse waste. The study will establish the potential role of abattoirs in the sustainable global energy transition.

1.2. Problem Statement

The overall objective of establishing the biogas plant was to generate biogas to be used in electricity generation besides treatment of slaughterhouse waste to mitigate environmental pollution. The generated electricity was meant to fully supplement the supply from the utility company. The electricity bills before installation of biogas plant stood at Kshs 30,000 monthly. However, even after the plant's installation, the slaughterhouse has continued to purchase power from KPLC at the average cost of ksh 10,000. This is a clear indication that the plant is not efficient enough to meet the energy needs of the slaughterhouse. Additionally, significant volume of the effluent still flows into the Kabuthi River hence not solving the problem of environmental pollution, which was to be solved by the establishment of this plant. The existing biogas plant has the following specifications: 3.5m^3 hydrolysis tank, 60.0m^3 anaerobic digester bag and 7.0m^3 overflow tank. The hydraulic retention time is 17 days and the average amount of biogas produced daily is 35.0 m^3. The design of the plant system, type of organic matter, the operating temperature and pressure in the digester, pH value of the substrate, and the plant's management are the key determining factors of the plant's overall efficiency. Modifying some of these factors could help increase the amount of biogas produced thus reducing fuel costs as well as environmental pollution by the slaughterhouse waste and maximize power generation. (Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; M. J. B. K. Kabeyi & O. A. Olanrewaju, 2022; Mitzlaff, 1988; Riley et al., 2020).

2.0. BIOGAS PRODUCTION AND USE

2.1. Biogas Properties and Production

Biogas is a gas produced by anaerobic digestion of organic matter such as dead plant and animal material, manure, sewage, or food waste. During the production process, three types of bacteria (cryophiles, mesophiles and thermophiles) transform the organic waste into biogas. The three types of bacteria are collectively known as methanogenic bacteria. Table one is a summary of the three classes of bacteria.

Table 1: Types of methanogenic bacteria (Arogo et al., 2018; Cucchiell et al., 2017)

Type of bacteria	Operating temperature
Cryophiles	12-24°C
Mesophiles	22-40°C
Thermophiles	50-70°C

From table 1, the optimum temperature for cryophiles is around 15°C, while that of mesophiles is 37°C whereas thermophiles have optimum temperature of 60°C, (Arogo et al., 2018; Cucchiell et al., 2017). This is illustrated in figure 3 below.

The cryophiles which operate roughly between 0 and 22^{o}C, mesophiles between 0 and 48^{o}C, and the thermophiles between 20 and 73^{o}C. Each of these classes of bacteria has own unique optimum operating temperature as shown in table 1 above.

The main constituents of biogas are methane, carbon dioxide, nitrogen, hydrogen and hydrogen sulphide (Bhardwaj & Das, 2017) as shown in table 2. The biogas produced is generally composed of the gases highlighted in table 2.

Table 2: Composition of biogas (Megwai & Richards, 2016)

Type of gases constituting biogas	**Percentage composition (%)**
Methane	50-75
Carbon dioxide	25-50
Nitrogen	0-10
Hydrogen	0-1
Hydrogen sulphide	0-3

From table 2 above, the composition of the substrate used in biogas processes has a significant impact on the volume of biogas produced. Fats/lipids generate more biogas per kg than other substrates such as carbohydrates. In addition, the concentration of methane and carbon dioxide in the produced biogas will also be dependent on the composition of the substrate. If the substrate contains a high proportion of protein, it can have a negative effect on the biogas generating process because the ammonia/ammonium mineralized during the degradation will inhibit the methane producing microorganisms. The concentration of ammonium-nitrogen should not exceed 3 grams per liter to maintain a stable and optimized production of biogas.

2.2. Biogas Plant

Organic waste is fed into the hydrolysis tank where mixing is done. The organic waste is composed of complex chains of carbohydrates, fats, and proteins. They are then broken down to lower organic compounds namely, sugars, fatty acids, and amino acids, which are the main stock of the methane-producing bacteria. The hydrolyzed waste is the fed to the anaerobic tank(Bhardwaj & Das, 2017; Cucchiell et al., 2017). The anaerobic digestion, the process starts with hydrolysis, followed by acidogenesis. Acidogenesis is a process whereby sugars, fatty acids and amino acids are converted to carbonic acids, alcohols, hydrogen, carbon dioxide and ammonia. This is then followed by acetogenesis, a process that breaks down the latter into hydrogen, acetic acid, and carbon. The three products are further broken down through methanogenesis to form methane and carbon dioxide, which are basically the components of biogas. The organic matter used should contain biodegradable matter to speed up hydrolysis. Most bacteria operate at a pH level range of 6.8-7.3(neutral conditions). The pH level is maintained around 7.0 by adding calcium hydroxide. The carbon to nitrogen ratio should range from 15-25. Inhibitory substances such as detergents, antibiotics, antiseptics, ammonia, volatile acids, and heavy metals should be kept away from the organic waste. Solid to moisture ratio should be high to use smaller fermentation space (AgSTAR, 2020; AL-Hawaja & AL-Mutairi, 2007; IRENA, 2018).

The hydraulic retention time (HRT) is the average time in which the sublayer for anaerobic digestion process is retained in the digester, in contact with biomass (bacterial mass). A short HRT produces a good rate of the raw material flux but reduces biogas productivity. A long HRT requires a higher reactor volume and consequently additional costs. The HRT is established depending on the digester volume and the loaded substrate volume in time unit. The high-speed anaerobic digesters which can maintain very long solids retention times (SRT) because of the bacterial biomass immobilization or overcrowding, works with short HRT and low costs (IRENA, 2018). The recommended maximum height of substrate in the digester should not exceed 3.5m and hence horizontal flow digesters are required. The rest of the area below the depth of 3.5m does not produce biogas. This is because the standard pressure required for biogas production should not exceed 350 mm of water (Zabalaga et al., 2020)

2.3 Biogas Production from Slaughterhouse Waste

Over a period, biogas production from slaughterhouse waste has proved to be a reliable renewable energy source, while at the same time reducing the environmental pollution by the slaughterhouse waste. This was the study conducted at the St. Martin biogas plant in upper Australia. This biogas plant in the village of St Martin is directly integrated into the largest abattoir of Austria. The company Grossfurtner slaughters 550,000 pigs and 50,000 cattle per year. It is the first biogas plant worldwide, which exclusively uses slaughterhouse waste as substrate for biogas production. All in all, 10,000 tons of blood, rumen content, colon content and grease separation material are used to produce 3.6 million kWh electricity and 3.6 million kWh heat per year. The aim of the project was the improvement of the economic and ecological performance of this abattoir. Two cost intensive areas in the company are the energy costs (natural gas, electricity) and the disposal costs for the slaughterhouse waste. By using the slaughterhouse waste as substrate for biogas production, Grossfurtner company can reduce the disposal costs and can cover approximately 33% of their electricity demand and 75% of their heat demand with renewable energies(M. Kabeyi & O. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a; Tanigawa, 2017).

Slaughterhouse residues are interesting substrates for producing biogas because disposal costs of most fractions are high. So many companies are interested in biogas technology to reduce disposal costs and energy costs. However, these fractions (like blood) have high nitrogen content and nitrogen (ammonia) can lead to microbiological inhibition and insufficient biogas production. So, slaughterhouse residues are generally used as co-substrate to limit ammonia content to maximum 5 g/l in the digester content. The biogas plant at Grossfurtner was the first biogas plant to use 100% slaughterhouse residues with ammonia content of more than 7 g/l and high degradation rates. Within several research projects, several parameters were changed and the whole process optimized to work satisfactorily at high nitrogen concentrations (Kabeyi & Oludolapo, 2020c, 2021; Oludolapo & Kabeyi, 2020).

3. Materials and Method

Nyongara slaughterhouse is in Dagoretti, located some 26km away from Nairobi City center. The authors through research assistants collected data from the operating slaughterhouse after obtaining permission from the organization through an official request. Both primary and secondary data were collected and used in the research and design. Primary data was collected through observation of the biogas plant design, document analysis and structured personal interviews with the manager and operational staff of the slaughterhouse. Secondary data was collected from available published literature on the slaughterhouse. The target population for this study was the slaughterhouse, employees, and other stakeholders (Nyongara slaughterhouse.) Official permission was sought from the slaughterhouse management to let the research and data collection be carried at the plant (Arogo et al., 2018). Data was analyzed and presented using descriptive statistics (Barasa, 2018; Jeremiahi, 2019; Moses, 2019). The data collected at Nyongara slaughterhouse were tabulated thoroughly checked for accuracy and completeness. The collected data was compared to that of an ideal biogas plant. The outcome of the comparison was discussed, and conclusions made. The conclusions drawn were then used to make recommendations to the Nyongara slaughterhouse management and make suggestion what other researchers can do further(Arogo et al., 2018; Cucchiell et al., 2017).

4. Results and Discussions

4.1. Organic Waste from The Slaughterhouse

This study showed that at Nyangera slaughterhouse, average number of animals slaughtered are 200 cattle, 400 goats and sheep. The organic waste from the slaughterhouse is composed of several components; animal dung, intestine contents, blood, wastewater and rejected pieces of meat. It has been found out that 20-50% of an animal slaughtered is not fit for human consumption. The average bulk density of fresh animal dung is 300kg/m^3 while that of slaughterhouse wastewater is 1000 kg/m^3 (Tanigawa, 2017).The waste generated from the four slaughtering units daily was determined as follows in table 3.

Table 3: Waste from the slaughterhouse (Author's analysis)

Type of waste	Amount(kg) produced daily	Amount fed into the digester daily	% Utilization
Solid waste (animal dung, intestine content, fats and rejected pieces of meat)	16,000kg	300kg	1.875%
Liquid waste (Blood and wastewater)	40m^3=40,000kg	2.5m^3=2,500kg	6.250%
Total	56,000kg	2,800kg	5.0%

From table 3, it is noted that biogas waste can be classified into liquid and solid waste and combined daily waste for the slaughterhouse is 56,000 kg.

In this study, the composition of wastewater from the slaughterhouse is from the company's own records. The composition of the waste by mass and volume is shown in table 4 below.

Table 4: Composition of organic waste fed into the digester (Kabeyi & Oludolapo, 2020c)

Type of waste	Average bulk density	Amount fed to digester daily		% Composition	
Unit of measurement	kg/m^3	Mass(kg)	Volume(m^3)	Mass (%)	Volume (%)
Animal dung, intestine content, fats and rejected pieces of meat	300 kg/m^3	300kg	1 m^3	10.57%	28.57%
Blood and wastewater	1000 kg/m^3	2500kg	2.5 m^3	89.23%	71.43%
Total		2800kg	3.5m^3	100%	100%
Mixing ratio					1:2.5

From table 4 above, it is noted that 89.23% of the waste by volume is blood and wastewater while 10.57% of the slaughterhouse waste is solid waste consisting mainly of dung, the animal intestines contents and rejected pieces of meat. Since 1kg of solid slaughterhouse waste generates 0.16m^3, then the 300kg solid waste from the Nyongara Slaughterhouse should be expected to produce the following volume of biogas daily.

If 1kg=0.160m^3 of biogas
300kg=? Let y=volume of biogas collected
300kg x 0.160m^3 =1kg x y
Y=48m^3 of biogas daily.

This implies that the expected volume of biogas produced at the Nyongara slaughterhouse biogas plant for the 300kg solid waste fed daily is 48m$^{3.}$ The solid waste to liquid waste ratio at Nyongera slaughterhouse is 300kg solid waste: 2.5m^3 of liquid waste. Therefore, if all the solid waste amounting to 16,000kg was fed to the digester, using the ratio stated above, the total liquid waste to be used should be: Liquid waste=16000kg/ (300kg/2.5m^3) =133.33m^3. This means that all the 40m^3 would be used and an additional 93.33m^3 needed to ensure the volumetric mixing ratio is maintained. If 300kg=48m^3 of biogas
16000kg=?
Y x 300kg=16000kg x 48m^3 hence, Y=2560m^3 of biogas production daily

i.) Hydrolysis tank

This is the tank where the solid waste and liquid waste are mixed by manual stirring. Manual stirring using a wooden stick is carried out by two workers at the biogas plant. This helps to homogenize the mixture and break the waste into smaller particles to enable it flow into the digester. The smaller the solid waste particles the easier it is for digestion to take place once the waste gets into the anaerobic tank. The tank has two sections each having a capacity of $3.5m^{3.}$ The hydrolysis tanks have two sieves at the outlet to prevent large indigestible particles from flowing into the digester. The hydrolysis tank is connected to a hot water system powered by 4 solar panels. The pipes carrying hot water pass through the tank to warm up the waste to speed up hydrolysis rate. Once mixed in the hydrolysis tank the substrate is retained for 48hours (2days) to break down to smaller particles. One of the tanks is opened daily to discharge $3.5m^3$ into the digester, and then fed with fresh substrate. The next discharge from the tank is after 48 hours.

ii.) The Digester

This is an air-tight tank where the three biogas forming processes take place. These processes are namely, acidogenesis, acetogenesis and methanogenesis. The following anaerobic tank conditions were collected at the Nyongara slaughterhouse biogas plant. The specifications of the existing digestor are shown in table 5 below.

Table 5: Property/conditions of the existing digester bag

Property/conditions of the digester bag	Value
Volumetric capacity of the digester bag	$60m^3$
Height of the digester bag	4.0 m
Length of the digester bag	5.0m
Width of the digester bag	3.0m
Temperature	34 °C
Pressure	400mm of water
The pH value	6.5
Feeding rate	$3.5m^3$ per day
Volume of biogas produced	Average of 40m3 daily.

From table 5, it is noted that volume of biogas produced daily averaged 40 m^3 at a pH of 6.5, digester temperature of 34^oC while the volume of the digester is $60m^3$.

The hydraulic retention time (HRT) can be calculated as follows.

Retention time=volumetric capacity of the digester/Feeding rate

$=60m^3 / (3.5m^3 /day) =17days$

The recommended maximum height of the substrate in the digester is 3.5m. In contrary, the Nyongera slaughterhouse substrate height goes up to 4.0m. This implies that the bacteria at the depth of 4.0m experience a pressure equal to 400mm of water.

Pressure due to substrate height=4m x $1000kg/m^3$ x$9.81m/s^2$=39,240Pa

This pressure exceeds the threshold height of 3.5m, where the pressure is computed below.

Pressure at 3.5m= (3.5m x 1000kg x $9.81m/s^2$) Pa =34,335Pa

This means that the substrate between the heights 3.5-4m does not produce biogas at all, meaning that 0.5m height of substrate goes to waste in every complete retention time. This wasted volume is calculated as shown below.

Volume=Area x height=0.5m x 3m x 5m=$7.5m^3$.

The measured temperature inside the digester was found to be 34 °C which is lower compared to the peak temperature in the mesophilic range. The peak temperature in the mesophilic range is 37°C.

The temperature is still lower than optimum temperature even though 9 solar panels constituting hot water system have been installed on the plant's rooftop. Five solar panels warm the digester while four of them the hydrolysis since the peak mesophilic temperature has not been attained, hence, the biogas production is not optimum. The main reason why it is difficult to attain the required temperature of 37°C is the fact that the digester is made of a thin-walled bag with no insulating materials. Atmospheric temperature can go down, especially at night, to as low as 16°C. Due to lack of insulation, the substrate temperature also reduces. When the Sun is up, the solar panels heat the water in the pipes, which in turns warms the hydrolysis and the substrate in the digester. However, due to low initial temperature it is always difficult to attain the recommended temperature of 37°C.This lowers the biogas productivity in the digester. The average pH level in the digester was established as 6.5, which is not within the acceptable pH value range suitable for biogas production. Acceptable enzymatic activity of methane-forming bacteria does not occur below pH value of 6.2. Most anaerobic bacteria, including methane-forming bacteria, perform well within a pH range of 6.8 to

7.3(M. Kabeyi & O. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a, 2022b; Kabeyi & Oludolapo, 2020a, 2020d).

4.2 Properties of Biogas Produced.

The biogas produced daily is on average 40m^3. Table 6 below summarizes the average composition of the biogas produced. The gas produced is channeled to the gas storage room which houses a 40m^3 gas storage bag. The calorific value of biogas can be estimated from the following physical and thermodynamic properties.

4.3. Power Generation at Slaughterhouse

The biogas plant has a 10 KW Three-phase ac 400V generator running on biogas. On average, this generator runs on biogas for 6 hours that is from 5:00-11:00am to produce 10KW. The generator operates using petrol and once it is running, the petrol is cut off. Due to the suction power developed, the biogas valve automatically opens thus letting biogas into the engine. When the generator is switched off, the biogas valve automatically closes. The generator provides electricity to light up the 4 slaughtering units as well as powering light slaughtering machines. The rest of the biogas produced is used by workers to cook food and to boil washing water needed in the 4 slaughtering units (M. Kabeyi & O. Olanrewaju, 2022; M. J. B. Kabeyi & A. O. Olanrewaju, 2022; Kabeyi & Oludolapo, 2020c).

From earlier calculations, 2.1444m^3 of biogas is equivalent to 1kg of petrol at 293K.

The density of petrol= 719.7 kg/m^3 which is 719.7kg/1000litres.

1 kg of petrol=1.389litres. Hence 1.389litres of petrol=2.1444m^3 of biogas.

The amount of biogas produced daily is 35 m^3, based on the above calculation this will translate to.

Y= (35m^3 x 1.389 liter)/2.144m^3 =22.68 liters of petrol.

4.4. Discussion and Interpretation of Results

Based on the above results, several interpretations can be made. These interpretations will help in drawing conclusions on the actual performance of the plant. This is achievable through comparison of the measured values to the standard values. The parameters to be considered are.

i. Retention time of the substrate in the digester
ii. Temperature inside the digester
iii. PH value of the substrate
iv. Height of the substrate in the digester
v. Pressure inside the digester
vi. Biogas productivity

The amount of slaughterhouse waste under consideration is 300kg.

Table 6: Comparison of measured values to optimum values (Smyth et al., 2010)

Property/conditions	Measured value	Optimum value	Deviation from optimum value
Retention time	17days	20 days	3 days
Temperature	34°C	37°C	3°C
PH value	6.5	7.0	0.5
Height of the substrate	4.0m	3.5m	0.5m
Pressure	4.0m of water	3.5m of water	0.5m of water
Biogas productivity (300kg of substrate)	35m^3	48 m^3	13m^3
Volumetric mixing ratio	1:2.5	1:1	

Based on the above comparisons shown in table 6, the measured values deviate from the recommended values as shown. This lowers the overall efficiency of the biogas plant and thus the expected volume of biogas produced is not realized. The amount of solid waste being utilized for biogas production is only 1.875%. On the other hand, only 6.25% of the liquid waste is utilized for biogas production. The total waste amounts to 56,000kg yet only 2,800kg is fed into the digester. The overall waste utilization is 5.0% which is quite insignificant compared to the 95% waste that goes unutilized. The main objective of the biogas plant, other than electricity production, was to serve as remedy to reduce pollution on the environment. It can also be noted that biogas produced is 35m^3 as opposed to 48m^3 expected outputs, a deviation of -13m^3.Therefore the current biogas production stands at 72.9% of the expected output.

4.5 Proposed Modifications

Having identified several factors preventing the biogas plant from 100% biogas productivity, the following recommendations are made for consideration by Nyongara slaughterhouse management on the types of modifications that can be adopted to boost biogas production and at the same time utilize all the waste from the abattoirs**.**

i.) Hydrolysis tank

To reduce pollution, all the liquid waste must be fed into the hydrolysis tank and eventually into the digester. Unlike in the current practice, solid waste: liquid waste volumetric mixing ratio must be 1:1. This will ensure higher biogas productivity. Since the liquid has higher pollution effect on the environment compared to solid, all the 40 m^3 must be utilized. With the mixing ratio of 1:1, the mass of solid waste to be used is.

40 m^3 x 300kg/ m^3=12000kg.

This will increase solid wasted utilization from 1.875% to 12000kg/ 16000kg x 100%=75%. The liquid to be utilized is 40 m^3 which is 100% of the waste. With the mixing ratio of 1:1, the total volume of hydrolysis tanks is (40 + 40) =80m^3. However, this volume makes it difficult to attain homogeneous mixing. Therefore, the volume is divided into two hydrolysis tanks (cylindrical in shape), each having a capacity of 40m^3. Each tank has a radius of 3.18m and height of 2m.

ii.) Digester

To attain the retention time of 20days with a substrate feeding rate of 80m^3 /day, the digester capacity should be 80m^3 /day x 20days=1600m^3.To achieve required insulation, the digester construction material should be concrete which is relatively cheaper and easy to maintain. The shape of the digester is to be cylindrical with a dome on top. The tank is of height 3.5m and radius of 12.06m. The height of 3.5m eliminates the need for stirring since methanogenic bacteria operate optimally between the depth ranges of 0-3.5m.

iii.) Overflow tank

The volume of effluent discharged from the digester is equal to that of the substrate fed into the digester. Therefore, the capacity of overflow tank is the same as that of hydrolysis tank, which is 80m^3. We recommend a height of 2m, length of 6.3m and width of 6.3m.

iv.) Heating system in the digester

The digester has an in-built heating system comprising of coiled stainless-steel pipes mounted in the digester. Hot water at the inlet temperature of 95 °C is circulated through the pipes and exits the digester at 37°C after heat exchange with the substrate. The substrate fed into the digester is 80m^3 and is assumed to be at the atmospheric temperature of 23°C. The working temperature in the digester required is 37°C. The heat capacity of the substrate is assumed to be equal to that of water. The hot water system is fitted with a thermostat set at 37°C to control the temperature not to rise or drop from the optimum temperature.

Calculation of the digester heat requirements.
Heat to be gained by 80m^3 substrate=Mass x heat capacity x temperature change
Mass of substrate; 1m3=650kg 80m^3=80 x 650kg=520000kg
Temperature change= 37°C-23°C=14°C=14K
Heat capacity=4200J/kg. K
Heat to be gained by 80m^3 substrate=52000kg x 4200J/kg. K x 14K =3.0576 x 10^9J
Heat lost by water to the 80^3 substrates= Mass x heat capacity x temperature change
Temperature change= 95°C-37°C=58°C=58K
Heat capacity=4200J/kg. K
Mass of water=?
Heat lost by water to the 80^3 substrates=Mass x (4200J/kg. K x 58K) = 3.0576 x 10^9J
Mass of water = (3.0576 x 10^9J) / (4200J/kg. K x 58K) =12551.724kg
Volume of hot water required in the pipes= (12551.724kg) / (1000kg/m^3) =12.551724m^3
Length of the pipe to be coiled in the digester, L.
Volume of water in the pipes=πr^2 L=12.551724m^3
Taking the radius of the pipe=0.05m, L= (12.551724m^3) / (0.05^2 π) =1598.135m
The circumference of the digester tank= 2 πr=2 x π x 12.06=75.7752m
The estimated number of coils= (Length of the pipe) / (circumference of the digester tank)
=1598.135m / 75.7752m =21 coils.

4.6. Conditions Under Which Biogas is Formed.

i.) PH value of the substrate in the digester

To attain optimum biogas production, the pH level must be maintained within the 6.8-7.3 range. Values of PH of below 6 and above 8 are restrictive to methane forming bacteria. This can be attained through addition of PH boosting reagents. The chemicals, sodium bicarbonate and potassium bicarbonate are perhaps the best chemicals of choice because of their desirable solubility, handling, and minimal adverse impacts within the digester. For example, overdosing of these chemicals does not cause the pH of the digester to quickly rise above the optimum. Also, of all the cations released by the alkali chemicals used for alkalinity addition, sodium and potassium are the least toxic to the bacteria in the digester. The reagents are mixed with the substrate in the hydrolysis tank.

ii.) Temperature in the digester

The temperature under which biogas production is optimum in the mesophilic range is 37°C. This temperature can be attained by hot water supplied to the digester and the hydrolysis tank by means of coiled pipe network in contact with the substrate to boost the temperature. The hot water system is fitted with a thermostat set at 37°C to control the temperature not to rise or drop from the optimum temperature (Energypedia, 2016; Haga, 2011).

iii.) The retention time.

The recommended retention time for slaughterhouse waste in the digester is 20 days to maximize on digestion of the substrate to achieve higher biogas production. This has been catered for in this recommended design.

Retention time = (volume of the digester)/ (feeding rate) = (1600m^3)/ (80m^3/day) =20 days

iv.) Plant performance comparison

The plant comparisons were done as shown in table 7.

Table 7: plant comparison (Bhardwaj & Das, 2017; Cucchiell et al., 2017)

Property	Current biogas plant	Proposed biogas plant	Deviation
Volumetric Mixing ratio of solid to liquid	1:2.5	1:1	
solid waste used	300kg	12000kg	+11700kg
Liquid waste used	2.5m^3 =2500kg	40 m^3=40000kg	+37.5 m^3=+37500kg
Retention time	17days	20days	+3days
Volume of biogas produced daily	40 m^3	1920 m^3	+1880 m^3
Temperature	34°C	37°C	+3°C
pH	6.5	7.0	+0.5
%Utilization of solid waste(x)= (solid used x100%)/total solid waste	X=(300kg/16000kg) x 100%=1.875%	X= (12000/16000) x 100%= 75%	+73.125%
%Utilization of liquid waste(x)= (liquid used x100%)/ total effluent waste	X= (2.5 m^3/40 m^3) x 100%= 6.25%	X= (40/40) x 100%= 100%	+93.75%
Overall % utilization of total waste (liquid + solid)	X=(2800kg/56000kg) x 100%=5.0%	X=(52000kg/56000kg) x 100%=92.86%	+87.86%

From table 7 above, it is demonstrated that the biogas productivity increases in the new modified recommendation to 1920m^3 from the initial 40m^3. This increase is attributed to the increase in size of the new plant that accommodates more waste. Solid waste utilization increases from 300kg to 12,000 kg, which is 75% of total waste, produced at the slaughterhouse each day. The effluent utilization is increased to 100% from very low utilization of 6.25%. The new modified plant addresses the issues of optimum temperature, optimum PH, and the pressure on mesophilic bacteria. Improvement of these factors enhances performance of methane forming bacteria, improving efficiency of the plant. Environmental pollution reduction which was a major concern and reason for establishment of the plant is attained in the new proposed plant. The total effluent waste is to be utilized in the new proposal; this ensures no emission to Kabuthi River. Overall, the new proposal addresses major concerns and maximizes biogas production and minimizes environmental pollution effect by slaughterhouse.

5. Conclusion

Slaughterhouse wastes is a potential source of bacterial, parasitic pathogens, prions, and, viral, organisms that can infect humans and animals hence need to be appropriately disposed of by rendering, alkaline hydrolysis (AH), composting, incineration and burning and, anaerobic digestion (AD). Slaughterhouse waste particularly that having high fat and protein is ideal for anaerobic digestion which leads to both methane, organic fertilizer, and sterilization. Based on the results and discussions in the previous sections, this study concludes that the Nyongara Biogas Plant produces an average of 35m^3 as opposed to the expected 48m^3 for every 300kg of solid slaughterhouse waste. This puts the plant's biogas productivity at 72.9%. Out of the total solid and liquid waste of 56,000kg from the slaughterhouse, only 2,800kg is utilized in biogas production. This means that only 5% of the total waste is utilized. Therefore, the reduction of pollution effect through establishment of the biogas plant is very insignificant. With the proposed biogas plant design, the utilization of the total waste increases from the current 2800kg to 52000kg which translates to 92.86% utilization. Environmental pollution by the slaughterhouse waste is therefore significantly reduced. Biogas production is also increased from 35m^3 to 1920 m^3 hence reducing power cost for the slaughterhouse. The objectives of this study which were to analyze the performance of the current biogas plant and modifying it have been fully achieved.

References

AgSTAR. (2020). *Anaerobic digester/Biogas system operator guidebook* (EPA 430-B-20-003). (A guidebook for operating anaerobic digestion/biogas systems on farms in the United States, Issue. https://www.epa.gov/sites/production/files/2020-11/documents/agstar-operator-guidebook.pdf

AL-Hawaja, O. M., & AL-Mutairi, H. (2007). A combined power cycle with absorption air conditioning. *32*(6), 971-982. https://doi.org/https://doi.org/10.1016/j.energy.2006.11.006

Arogo, J., Ignosh, J., & Bendfeldt, E. (2018). Biomethane production technology. Article 442-881. https://www.pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/442/442-881/BSE-240.pdf

Barasa, M. J. K. (2018). Transformational Vs Transactional Leadership with Examples. *International Journal of Business & Management*, *6*(5), 191-193. . http://www.internationaljournalcorner.com/index.php/theijbm/article/view/129786/90079

Bhardwaj, S., & Das, P. (2017). A Review: Advantages and Disadvantages of Biogas. *International Research Journal of Engineering and Technology (IRJET)*, *4*(10), 890-893.

Cucchiell, F., D'Adamo, I., & Gastaldi, M. (2017). Biomethane: A renewable resource as vehicle fuel. *Resources*, *6*(58).

Energypedia. (2016). *Biogas plant used for power generation.png*. Energypedia Retrieved 16 December 2020 from https://energypedia.info/wiki/Electricity_Generation_from_Biogas

Franke-Whittle, I. H., & Insam, H. (2013). Treatment alternatives of slaughterhouse wastes, and their effect on the inactivation of different pathogens: a review. *Critical reviews in microbiology*, *39*(2), 139-151. https://doi.org/10.3109/1040841X.2012.694410

Haga, N. (2011). *Combustion engine power plants*. https://www.wartsila.com/docs/default-source/power-plants-documents/downloads/white-papers/general/wartsila-bwp-combustion-engine-power-plants.pdf

IRENA. (2018). Biogas for road vehicles: Technology brief. In i. R. E. Agency (Ed.). Abu Dhabi.

Jeremiahi, M. B. K. (2019). Evolution of Project Management, Monitoring and Evaluation, with Historical Events and Projects that Have Shaped the Development of Project Management as a Profession. *International Journal of Science and Research (IJSR)*, *8* (12). https://doi.org/10.21275/ART20202078

Kabeyi, M., & Olanrewaju, O. (2022). Slaughterhouse waste to energy in the energy transition with performance analysis and design of slaughterhouse biodigestor. *Journal of Energy Management and Technology*, *6*(3), 188-208. https://doi.org/http://dx.doi.org/10.22109/jemt.2021.292954.1309

Kabeyi, M. J. B. (2019). Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, *5*(8), 53-95. https://doi.org/10.31695/IJASRE.2019.33408

Kabeyi, M. J. B. (2022). Sustainability in the energy transition to renewable and low carbon grid electricity generation and supply. *Frontiers in Energy Research*. https://doi.org/https://doi.org.10.3389/fenrg.2021.743114

Kabeyi, M. J. B., & Olanrewaju, A. O. (2022, March 7-10, 2022). *Biogas production and applications in the sustainable energy transition* International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey, .

Kabeyi, M. J. B., & Olanrewaju, O. A. (2021, 7-8 Oct. 2021). Conversion of a Flash Power Plant to Organic Rankine System for Olkaria Geothermal Power Plants. 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME),

Kabeyi, M. J. B., & Olanrewaju, O. A. (2021a, March 7-11, 2021). *Development of a cereal grain drying system using internal combustion engine waste heat* 11th Annual International Conference on Industrial Engineering and Operations Management Singapore. http://www.ieomsociety.org/singapore2021/papers/188.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2021b, March 7-11, 2021). *Performance analysis of a sugarcane bagasse cogeneration power plant in grid electricity generation* 11th Annual International Conference on Industrial Engineering and Operations Management Singapore. http://www.ieomsociety.org/singapore2021/papers/201.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022a). Biogas Production and Applications in the Sustainable Energy Transition. *Journal of Energy*, *2022*(8750221), 43. https://doi.org/https://doi.org/10.1155/2022/8750221

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022b, April 5-7, 2022). *Conversion of diesel and petrol engines to biogas engines as an energy transition strategy* 4th African International Conference on Industrial Engineering and Operations Management, Nsukka, Nigeria. https://ieomsociety.org/proceedings/2022nigeria/448.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022c). Geothermal wellhead technology power plants in grid electricity generation: A review. *Energy Strategy Reviews*, *39*, 100735. https://doi.org/https://doi.org/10.1016/j.esr.2021.100735

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022, 9-10 December 2021). *Relationship Between Electricity Consumption and Economic Development* International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town-South Africa. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9698413

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). slaughterhouse waste to energy in the energy transition with performance analysis and design of slaughterhouse biodigestor. *Journal of Energy Management and Technology*, *1*(1), 23. https://doi.org/10.22109/JEMT.2021.292954.1309

Kabeyi, M. J. B., & Olenwaraju, A. O. (2020, December 7-10, 2020). *Development of a Biogas Plant with Electricity Generation, Heating and Fertilizer Recovery Systems* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://www.ieomsociety.org/harare2020/papers/82.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020a, 5-7 December 2020). *Development of a Biogas Plant with Electricity Generation, Heating and Fertilizer Recovery Systems* 2nd African International Conference on Industrial Engineering and Operations Management, IEOM Society International. http://ieomsociety.org/harare2020/papers/82.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020b, 14-17 December 2020). *Managing Sustainability in Electricity Generation* 2020 IEEE International Conference on Industrial Engineering and Engineering Management, Singapore, Singapore. https://ieeexplore.ieee.org/document/9309994

Kabeyi, M. J. B., & Oludolapo, A. O. (2020c, 5- 7 December 2020). *Optimization of Biogas Production for Optimal Abattoir Waste Treatment with Bio-Methanation as Solution to Nairobi Slaughterhouses Waste Disposal* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://ieomsociety.org/harare2020/papers/83.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020d, 5- 7 December 2020). *Optimization of Biogas Production for Optimal Abattoir Waste Treatment with Bio-Methanation as Solution to Nairobi Slaughterhouses Waste Disposal* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://ieomsociety.org/harare2020/papers/83.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020e, December 7-10, 2020). *The Potential of Grid Power Generation from Municipal Solid Waste for Nairobi City* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://www.ieomsociety.org/harare2020/papers/81.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020f, 5-7 December 2020). *The Potential of Power Generation from Municipal Solid Waste* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://ieomsociety.org/harare2020/papers/81.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2021). Central versus wellhead power plants in geothermal grid electricity generation. *Energy, Sustainability and Society 11*(7), 23, Article ESSO-D-20-00011R4. https://doi.org/https://doi.org/10.1186/s13705-021-00283-8

Kabeyi, M. J. B. K., & Olanrewaju, O. A. (2022, 25-27 Jan. 2022). The Use of Smart Grids in the Energy Transition. 2022 30th Southern African Universities Power Engineering Conference (SAUPEC),

Megwai, G. U., & Richards, T. (2016). A Techno-Economic Analysis of Biomass Power Systems Using Aspen Plus. *International Journal of Power and Renewable Energy Systems (IJPRES)*, *3*(2), 25-36. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1056211&dswid=8509

Mitzlaff, K. (1988). *Engines for biogas*. (3-528-02032-6). Eschborn, Germany: Vieweg & Sohn Verlagsgesellschaft mbH Retrieved from https://biogas.ifas.ufl.edu/ad_development/documents/Engines%20for%20biogas.pdf

Moses, J. B. K. (2019). Project and Program Evaluation Consultancy With Terms of Reference, Challenges, Opportunities, and Recommendations. *International Journal of Scientific and Research Publications*, *9*(12), 171-194. https://doi.org/http://dx.doi.org/10.29322/IJSRP.9.12.2019.p9622

Oludolapo, A. O., & Kabeyi, M. J. B. (2020, December 7-10). *Design and Modelling of a Waste Heat Recovery System for a 250KW Diesel Engine for Cereals Drying* 2nd African International Conference on Industrial Engineering and Operations Management Harare, Zimbabwe. http://www.ieomsociety.org/harare2020/papers/78.pdf

Riley, D. M., Tian, J., Güngör-Demirci, G., Phelan, P., Villalobos, J. R., & Milcarek, R. J. (2020). Techno-Economic Assessment of CHP Systems in Wastewater Treatment Plants. *Environments*, *7*(10), 74. https://www.mdpi.com/2076-3298/7/10/74

Selormey, G. K., Barnes, B., Kemausuor, F., & Darkwah, L. (2021). A review of anaerobic digestion of slaughterhouse waste: effect of selected operational and environmental parameters on anaerobic biodegradability. *Reviews in Environmental Science and Bio/Technology*, *20*(4), 1073-1086. https://doi.org/10.1007/s11157-021-09596-8

Sims, R. E. H., Rogner, H., & Gregory, K. (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy*, *31*(13), 1315-1326. https://doi.org/https://doi.org/10.1016/S0301-4215(02)00192-1

Smyth, B. M., Smyth, H., & Murphy, J. D. (2010). Can grass biomethane be an economically viable biofuel for the farmer and the consumer? *Biofuels and biorefining 4*(5), 519-537. https://doi.org/https://doi.org/10.1002/bbb.238

Tanigawa, S. (2017). Biogas: Converting Waste to Energy. Retrieved 15 December 2020, from https://www.eesi.org/files/FactSheet_Biogas_2017.09.pdf

USDA. (2019). *Economics of Anaerobic Digesters for Processing Animal Manure*. https://lpelc.org/economics-of-anaerobic-digesters-for-processing-animal-manure/

Ware, A., & Power, N. (2016). Biogas from cattle slaughterhouse waste: Energy recovery towards an energy self-sufficient industry in Ireland. *Renewable energy*, *97*, 541-549. https://doi.org/https://doi.org/10.1016/j.renene.2016.05.068

Zabalaga, P. J., Cardozo, E., Campero, L. A. C., & Ramos, J. A. A. (2020). Performance analysis of a Stirling engine hybrid power system. *Energies*, *13*(4). https://doi.org/https://doi.org/10.3390/en13040980

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