Slaughterhouse waste to energy in the energy transition with performance analysis and design of slaughterhouse biodigestor

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Slaughterhouses produce huge quantities of different solid wastes and wastewaters which must be treated and disposed of to prevent health and environmental disasters and compliance with the environmental legislation. Waste disposal costs are high while the various processes have high electricity and heat energy demand hence the need for cheap sustainable energy sources. A performance analysis of an operating slaughterhouse was carried out with the objective of identifying challenges, opportunities and improvement measures through operation and proposal of an optimum design of the biogas plant. The facility slaughters an average of 200 cows and 400 sheep per day producing an average of 16,000 kg of solid waste and 40 m^3 of wastewater. The study showed that out of the total solid and liquid waste of about 56,000 kg from the slaughterhouse, only 2,800 kg is utilized in biogas production leaving out 53,200 kg of waste untreated by the biogas digestor. This research proposes the construction of an 80 m^3 capacity hydrolysis tank, 1,600 m^3capacity digester tank and a 2,000 m^3 biogas storage bag for the increased biogas production. Retention time would have to be increased to 20 days from 17 days and substrate PH level increased to 7.0 from average of 6.5. The proposed design will increase biogas production from current 35 m^3 to 1,920 m^3 and increase solid wasted utilization increase from 1.875% to 75% and that of liquid waste from 6.25% to 100%. Production of biogas and electricity will contribute to greenhouse gas emissions mitigation as one of the wastes to energy pathways in the energy transition. The study concludes that slaughterhouse waste to energy conversion has an important role to play in the sustainable energy transition and a cleaner environment.

keywords: *Anaerobic digestion, abattoir waste, digester design, biogas production, optimum conditions for digestion, waste to energy.*

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1. INTRODUCTION

Slaughterhouses have many processes that are energy intensive that require electricity and heat for operations. They also encounter high waste disposal costs for the various animal by-products (ABP) which makes both energy and disposal costs the main cost drivers in abattoirs [1]. Environmental regulations in the European Union and other countries require comprehensive treatment and disposal of slaughterhouse wastes, yet the abattoirs produce huge quantities of wastes that must be treated using various acceptable techniques[2]. Animal husbandry and slaughterhouse waste have significant potential for biogas production and generation of an extra revenue stream and supply of energy for internal use [3, 4]. Countries need access to sustainable energy resources for sustainable development and economic prosperity with energy being used to improve the quality of life. Energy is an important input as a factor of production and hence it affects the cost of production of goods and services. Energy is also needed to realize almost all the Sustainable Development Goals (SDGs) [5–7]. Conversion of slaughterhouse waste to biogas and electricity reduces the cost of waste treatment, inactivates pathogens and production of fertilizer in addition to clean electricity and heat for use in the facility with excess electricity for sale to the public grid hence creating additional revenue stream and plays a significant role in the energy transition to low carbon electricity and energy mix[8, 9]. Waste to energy conversion reduces the over-reliance on fossil fuels for heat and electricity applications [5–10]. There is a global increase in demand for renewable sources of energy because of commitment by various nations to reduce their carbon emissions [9, 11]. Abattoirs produce wastes that are rich in organic contaminants and nutrients hence have huge potential for recovery of waste and energy generation through biodegrading and anaerobic digestion [12]. A common practice in many countries is to use human and organic waste to produce biogas for heat and electricity applications [13]. Similarly, slaughterhouse waste like blood, hind gut, fat scrubber content, and stomach content which is not meant for further processing of useful products can be used for production of biogas which then can be used to produce hot water and electricity for use in the facility with excess electricity being sold to the grid [8]. With the current global effort to fight environmental degradation and climate change due to greenhouse gas emission in energy and power generation, need for enhanced global food security and stable ecology to realize sustainable development [14–16], there is growing shift and need for green sources of energy and waste to energy conversion systems [11, 15]. Abattoirs generate significant quantities of waste which can pollute the environment and present significant health and environmental risks [17, 18]. The bio-digestion of the abattoir waste is an important disposal strategy for slaughterhouse waste [19, 20]. The biogas yield is influenced by a number of factors like the pH, substrate characteristics, C/N ratio (carbon to nitrogen ratio), hydraulic retention time and substrate mixing and digestion temperature [21]. The process produces biogas which can be used for heating and as fuel for biogas engine generators for electricity generation as well as digestate which can be used as organic manure[19, 22]. A typical slaughterhouse needs electricity for lighting and light machines operation and hot water for cleaning. Production of biogas from the waste will bring significant benefits in terms of savings in electricity bills for lighting and heating while excess power and even biogas can be sold thus creating additional revenue streams [10, 23]. Therefore, with concerns over climate change and a clean environment and scarcity of clean energy resources, slaughterhouse waste to energy conversion is an attractive option in the energy transition [14, 24–26]. Most developing countries have a serious challenge with disposal of slaughterhouse waste. As a result, the waste is disposed of in open dumpsites while liquid waste is disposed in open channels and surface water bodies like rivers which endangers aquatic and human life [20, 27]. Some is released to wastewater system often untreated hence further overloading the poorly managed system. Slaughterhouse waste can increase in the biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids, the pH, the temperature, water turbidity, and deoxygenation of water bodies[17, 28]. The overall objective of establishing the biogas plant at Nyongara slaughterhouse facility was to generate biogas for use in electricity generation besides treatment of slaughterhouse waste to mitigate environmental pollution and meet environmental standards imposed by National Environment Management Authority (NEMA) [28]. The generated electricity was meant to fully supplement the power supply from the utility company i.e. Kenya Power[10]. The electricity bills before installation of biogas plant stood at Kshs 30,000 (US $ 300) monthly. The problem of high electricity bills was however not completely solved as the, the slaughterhouse continued to purchase power from Kenya Power at the average cost of Kshs 10,000 (US $ 100) which was much lower than the initial average bills[20]. This is a clear indication that the plant is not efficient enough to meet the energy needs of the slaughterhouse as initially anticipated. Additionally, amount of the effluent still flows into the Kabuthi River which is a tributary of the Nairobi River hence the challenge of environmental pollution still exists [10, 20]

The existing biogas plant has the following specifications: 3.5 m^3 hydrolysis tank, 60.0 m^3 anaerobic digester bag and 7.0 m^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[10, 20]. Biogas has various applications which include use as a fuel for heating purposes such as cooking and boiling, use as a fuel in internal combustion engines, power generation by use as fuel for powering engines, while the digestate can be used as a fertilizer or organic manure[27, 29]. These wide applications act as an incentives for increased production at Nyongara slaughterhouse plant. This study reviews biogas production from slaughterhouse waste and a case study of an operating biogas plant for a slaughterhouse in Kenya and proposes an optimum bio digestion system. This study targeted Nyongara slaughterhouse based in Dagoreti, 26 KM away from Nairobi. It is one of the many slaughterhouses in Nairobi and its surrounding. The slaughterhouse employs about 5000 people and generates about 56,000 kg of solid waste and 60,000 liters wastewater per day. It is one of the major meat suppliers in both Nairobi and Kiambu counties[10, 30]. The overall objective of the study was to identify measures necessary to maximize the use of slaughter wise waste for biogas and electricity generation for internal use and export of the excess power to the grid. The study involved a performance analysis and proposed an optimum biogas plant that can digest most of the waste and maximize biogas production and minimize environmental pollution by increased utilization of waste and higher biogas productivity[31, 32].

2. SLAUGHTERHOUSE WASTE GENERATION AND DISPOSAL

Slaughterhouses are livestock meat processing facilities that engage in slaughtering animals for meat and supply of raw materials for other industries and products like tanneries, rendering or fat extraction plants, hides, pet food, gelatin, and other meat products like sausages[33]. Slaughterhouse operations and processes are quite similar globally. The main activities in activities and stages in animal slaughtering include animal receiving, temporary stocking or keeping the livestock, slaughtering of the animals, animal carcass dressing, carcass chilling, boning of carcass, and product packaging which produces significant animal products wastes and wastewater. Other critical process in slaughterhouses is freezing of finished animal carcass and packed products. Other slaughterhouse processes are rendering, skins drying, wastewater treatment of wastewater and product & waste transportation. Most of these processes need energy inform of electricity and heat[33]. Additionally, investments should not only meet regulations and quality requirements, but should also make, technical and socio-economic sense to the stakeholders[34–36]. This calls for prudent project planning and execution and good corporate governance practices. Safe, efficient, and cost-effective slaughterhouse waste disposal is one of the major challenges facing the agricultural and industrial sectors[37]. Slaughterhouses produce substantial quantities of biodegradable organic waste from the slaughter of animals like sheep, goats, cattle, pigs, poultry, and buffaloes. These waste, if not well managed and treated can form the breeding ground for pathogens. They also attract flies, pigs, birds, dogs, and other vermin. Burning and burying of slaughterhouse waste is wasteful as useful biomass is lost, hence the need to adopt measures that can convert the wastes and byproducts of slaughterhouses to useful applications like waste to energy conversion[20].

A. Waste generation

The continuous growth in global population, urbanization and economic growth and hence improvement in peoples economic wellbeing and standard of living has led to ever growing demand for meat and meat products, poultry and livestock whose consumption leads to release of significant waste quantities [38]. The total waste generation by a slaughterhouse is influenced by the recovery ability of the facility and is further guided by the consumer customs or behavior[9, 39]. All parts of an animal having some feasible application or use are referred to as byproducts and not slaughterhouse wastes[38]. Therefore disposable waste varies from one slaughterhouse to another [40]. Slaughterhouse waste can be classified into solid waste and liquid waste. Slaughterhouse solid waste is broadly classified into vegetable matter and animal matter. Almost all wastes of slaughterhouses can be utilized with varying degree of byproduct recovery based on handling and processing costs, market availability and access, and quantities recoverable[26, 41]. Disposal methods for slaughterhouse waste include composting, bio methanation and rendering, incineration, with selection of appropriate method being mainly dependent on type of wastes and its recoverable available quantity[40]. The terms byproducts and offal are generally used to denote every part not included in a dressed carcass. There are two types of slaughterhouse by-products namely, edible, and inedible. Edible byproducts include organs like kidneys, the heart, brain, liver, gullet while inedible by-products include hooves, hair, skins, hides, horns, bristles, gall bladder, ears, skin etc. The slaughterhouse byproducts can used as edible meat or may be processed to various commercial be products and applications while all unrecovered components constitute solid wastes. The generation of slaughterhouse waste is largely influenced by ability of the facility to recover by-products which further depends on customs of the consumers. Therefore, the quantity of slaughterhouse wastes varies from facility to facility and location to location. The main components of solid wastes are ruminal, the stomach and contents of the intestinal. Additionally, the stomach and large intestine are disposed of as waste in many slaughterhouses. The soft meat portions like lungs and pancreas are often collected in large slaughterhouses for sale to animal feed processors while this offal is disposed as waste in medium and small slaughterhouses. The animal horns and hooves are generally collected for sale[20, 40].On average, bovines generate 275 kg/ton of live weight killed (TLWK) which accounts for about 27.5% of the live animal weight. For goats and sheep, waste produced is about 170 kg per ton of live weight killed which is about 17% of animal weight. Pigs generate about 2.3 kg/head as waste which is about 4% of the animal weight. This is summarized in table 1 below. Where TWLK= Total live weight of animal killed From table 1, it is noted that bovines which include cattle and buffalos generate the highest percentage of waste per ton of live weight killed at 27.5% followed by goats and sheep at 17% while the least solid waste is generated by pigs at just 4% of the weight of animals. Average waste per animal killed is 83 kg for bovines, 2.5 kg for goats and sheep and 2.3 kg per pig slaughtered.

B. Composition of slaughterhouse waste

The main component of slaughterhouse waste is biodegradable matter. The characteristics of solid wastes from goat and sheep slaughtering are given in Table 2. Where mg/g = milligram per gram of waste. From table 2 above, it is noted that the slaughterhouse waste from goats and sheep has high moisture content of about 69.45% with the solids constituting 30.55%. Of the total solids, the volatiles are 87.95% while 12.05% constitute fixed solids. Organic carbon is 23.32%, while phosphorus and potassium account for 6.9 and 4.19 mg/g of fixed solids.

C. Slaughterhouse Waste Classification Disposal

The disposal of slaughterhouse waste is standardized in most countries. In the European Union (EU), legislation is provided to guide the disposal of slaughterhouse waste. The waste is classified into three main categories that require specific and unique treatment. The three main categories of animal by-products are
a) Category 1
This constitutes high risk material which may be from infected animals, and international catering. This waste material is not allowed to be treated by composting or anaerobic digestion[26, 42]. Other high risk animal byproducts include animals slaughtered with the objective of stopping disease spread, animal tissues collected from category one wastewater systems, specified risk materials, wild animals suspected to be infected with infectious diseases, and zoo as well as pet carcasses[26].
b) Category 2
This is the medium-risk animal by-products like those from diseased animals, manure and digestive tract contents which are not used in composting and biogas plants, unless except after rendering 133^{o}C at 300 kPa, for at least 20 minutes which is the EU pressure-rendering standard or sterilization[26, 42]. Other medium risk animals are catering waste except for catering waste from international transport, fish and meat from manufacturers and retailers, byproducts from animals that die from other means other than slaughtering, animal tissue collected from category production plants and related waste treatment processes, and foodstuffs from material of animal origin[26].
c) Category 3
This is animal byproduct or waste is low risk like catering residues, edible meat, precooked foods, etc. Which are for food consumption[26, 42]. These products must heated to at least 70^{o}C for 1 hour under closed conditions in a closed system conditions[42]. Other low risk waste under this category like feathers, hooves, horns, shells, fish, and other sea animals, milk eggs and uninfected animal products[26].

i) Rendering

Rendering is among the oldest and efficient process that facilitates recovery in form of fat and protein flour[26]. Rendering provides a sustainable solution to slaughterhouse waste by allowing consideration of profitability and productivity through processing and recycling some animal parts for various applications[37]. These options include rendering which applies to bones, inedible offal, blood and trimmings by converting them to more valuable products, while land spreading applies to sludge, paunch, and lairage[43]. In rendering facilities, the selected animal parts are sterilized usually by steaming to eliminate disease risks before shredding to produce protein rich feeds[37]. The benefits of rendering include cost efficiency hence saves in disposal costs, produces useful products instead of destroying and in the process leads to extra revenue and improves profitability of slaughterhouses.

Table 1. Quantity of solid waste from different animals [20, 40]

Animal	Total waste/Animal	Waste /tons of live animal	Percentages/TWLK
Bovine e.g., cattle	83	275	27/5
Goat/sheep	2/5	170	17
pig	2/3	40	4

Table 2. Characteristics of slaughterhouse waste from goat and sheep slaughterhouse [40]

	Parameter	unit	Value
1	Moisture content	%	69/45
2	Total solids	%	30/55
3	Volatile solids content	%	87/95
4	Fixed solids composition	%	12/05
5	Organic carbon content	%	23/32
6	Nitrogen content	%	2/71
7	Phosphorus Content	mg/gram of waste	4/19
8	Potassium content	mg/gram of waste	6/9

ii) Landfilling
Substantial amount of waste in dry form can be picked by dumpster pick up services for disposal in landfills. The material ought to be dry and should not create unsanitary conditions in dumpsites[44]. Although methods like incineration and composting reduces the volume of waste and pathogenic threat, some material will always be left for landfilling[44].
iii) Incineration
Incineration reduces slaughterhouse waste to ash and bone which then can be disposed of in landfills as municipal solid waste (MSW) or it can be spread on land based on a nutrient management strategy. A nutrient plan enables application of waste for soil fertility improvement. This process must be controlled because soils vary in nutrient content and need[44]. Incineration of animal byproducts (ABPs) is considered the most expensive mainly because of the high moisture content making it some of the most difficult material to burn[26].
iv) Composting
Composting is an aerobic process in which organic materials are degraded by successive groups of microorganisms. The process success depends on the availability of high microbial diversity. In composting, different microbial communities predominate during four consecutive phases which involve mesophilic, thermotolerant, and thermophilic aerobic microorganisms. Important parameters in composting are the temperature, pH, aeration, moisture, and substrate availability. Composting leads to temperatures that inactivate or destroy and reduce many pathogens. However, the temperatures cannot lead to complete sterilization of waste as some room is left for survival of some pathogens depending on temperature reached and time taken to heat the waste[42]. Different countries may have different requirements for composting slaughterhouse waste. However, a of 65°C for at least six consecutive days or two 3-day periods with temperature greater than 65 °C may be considered sufficient. An average temperature of 55–60 °C for 1–2 days can reduce e viruses, bacteria, and protozoa, to an acceptable level. However, this may not be appropriate for endospores that are produced by spore-forming bacteria. In composting, the pH can reach and exceed 8 which can inactivate of several pathogenic microorganisms. Antibiotics produced by various microorganisms in the compost also contribute to inactivation of pathogenic microorganisms. Composting can potentially serve as an acceptable method of disposal of slaughterhouse wastes. Composting help serve the role of post-treatment of anaerobic digestion wastes leading to better and more complete feedstock digestion and enriches the compost in terms of required nutrients besides reducing the pathogenic load of the abattoir wastes[45].
v)Alkaline hydrolysis process
In alkaline hydrolysis, sodium, or potassium hydroxide is used as a catalyst for the hydrolysis of proteins, nucleic acids, carbohydrates, lipids, and other biological material to form a sterile aqueous solution of amino acids, small peptides, soaps, and sugars. Alkaline hydrolysis is done at a higher pressure and temperature to accelerate the hydrolysis. Pathogens are inactivated by heating to a temperature of 100 °C and pressure of 103 kPa for a duration of 3 hours. Carcasses must be heated to 150 °C and pressurized at 486 kPa for 6–8 hours to destroy the prion containing material. Alkaline Hydrolysis done at 100 °C, pH ≈10, 120 kPa and for 60min was reported to destroy all pathogens. An alkaline pretreatment with NaOH can also be used to enhance biogas production from the slaughterhouse waste[45].
vi) Anaerobic digestion of animal waste
The anaerobic digestion of slaughterhouse waste involves word treatment of the animal by-products while at the same time producing useful energy in the form of biogas that can be used for electrical and thermal applications while the substrate or solid waste can be used as a fertilizer to improve crop husbandry[42]. It is defined as a biological process by which organic or biological wastes is digested in oxygen deficient environment to produce biogas and sludge. Inactivation of pathogens is the main concern over anaerobic digestion of abattoir waste. The solution to this serious concern with legal and health implications is to carry out secondary heat treatment process of feedstock by processes like composting, pasteurization, and maintenance of minimum residence period for the digestate as an additional measure [26, 46]. Different countries may have different requirements for treatment of biodigester feedstock for anaerobic digestion. For example, the Swedish law requires biogas plants that use animal waste to pasteurize the incoming substrate at 70 °C for one hour before digestion. Anaerobic digestion can be done under mesophilic or thermophilic conditions where digestion is done at average temperature of 35 °C for mesophilic and average of 60 °C under thermophilic conditions. They therefore require different residence conditions to destroy or denature pathogens. The hydraulic residence time for mesophilic process will typically run for 15–30 days, while a thermophilic process has hydraulic residence time of 12–14 days. The advantage of mesophilic anaerobic digestion is that it is less sensitive to changes in process

parameters as compared to thermophilic processes. However, the gas yield is lower and with a greater pathogen risk. The main challenge of anaerobic digestion of waste is the methane producing microorganisms are quite sensitive to thermal changes and variations as low as 2 °C can cause adverse effects on mesophilic anaerobic digestion processes. Comparison of mesophilic and thermophilic processes shows that thermophilic anaerobic digestion is superior and hence preferable because the process yields higher methane output, higher waste throughput, and a better pathogen inactivation capacity compared to mesophilic anaerobic digestion. However, the thermophilic digestion process is expensive and requires a higher degree of process monitoring compared to mesophilic anaerobic digestion[42]. Studies show that anaerobic digestion can inactivate viruses with the rate of inactivation being influenced by the type of virus, the digestion temperature, and duration of digestion or hydraulic residence time. For effective inactivation of bio-digested material, additional thermal treatment is needed for pathogens like the spore-formers. The European Commission Regulations (EC) no. 1774⁄2002 and no. 208⁄2006 prescribes a 70 °C/60-minute pasteurization step for slaughterhouse waste before landfilling. Accumulation of ammonia remains a serious challenge for high lipid and protein containing slaughterhouse waste products. This is because accumulation of ammonia inhibits the degradation of proteins and long chain fatty acid accumulation from the breakdown of lipids. Additionally, lipids can form floating aggregates and foam causing stratification challenges as a result of adsorption of lipids into the biomass[45]. This implies that due to high lipid and protein content, slaughterhouse waste needs control of ammonia formation and foaming.

D. Biogas Production

Biogas is made 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 namely the cryophiles, mesophiles and thermophiles transform the organic waste into biogas[13]. The three types of bacteria are collectively known as methanogenic bacteria. Table 3 below is a summary of the three classes of bacteria and their optimum working temperature. From table 3, it is observed that cryophiles

Table 3. Types of methanogenic bacteria [47, 48]

Type of bacteria	Operating temperature	Average temperature
Cryophiles	12-24 C	18 C
Mesophiles	22-48 C	35 C
Thermophiles	50-70 C	60 C

operate in the temperature range of 12 to 24^{o}C, while the optimum temperature for cryophiles is an average of about 18^{o}C. The mesophiles are active between 22 and 48^{o}C or average of 35 oC whereas thermophiles are active between 50 and 70^{o}C or an average of average temperature of 60^{o}C[47, 48]. This operating range of temperature for the three classes of bacteria is illustrated in figure 1 below.

From figure 1, it is noted that there are three types of bacteria biogas used in production. The cryophiles operate between 0 and 22 oC, mesophiles between 0 and 48 oC, and the thermophiles between 20 and 73^{o}C. Each of these classes of bacteria have their own unique optimum operating temperature as shown in table 3 above. However, methane production should be carried out

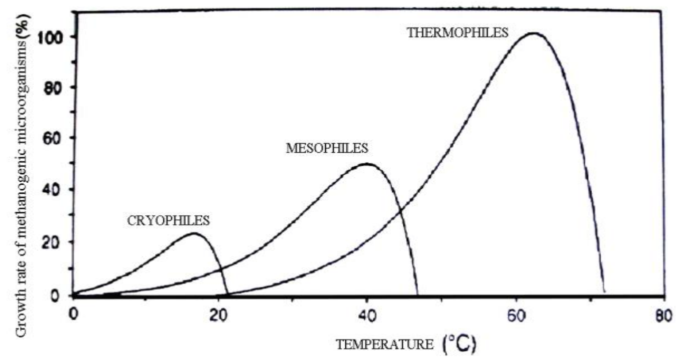

Fig. 1. Figure 1: Graph showing optimum temperature for methanogenic bacteria[49]

between 30 and 40 oC with optimum temperature being about 40 oC [13].

E. Biogas Properties

The main constituents of biogas are methane, carbon dioxide, nitrogen, hydrogen and hydrogen sulphide[49] . The quality of biogas is influenced by the composition of CO2, H2S, CH4 while the energy content of biogas is between 6.0 and 7.5 kWh compared to coal gas whose calorific value go 9.9 kWh[50]. Table 4 presents the genera composition of biogas. From table 4,

Table 4. Average composition of biogas [47, 49, 51, 52]

	Element	Composition (%)
1	Methane	25-80%
2	Carbon dioxide	2-45%
3	Nitrogen	0-10%
4	Ammonia	0-0.05%
5	Moisture	2-8%
	Hydrogen	0-1%
6	Hydrogen sulphide	0-3%
7	Oxygen	0-3%
8	Ammonia	0-0.5%
9	R2SiO	O-0.5 mg/m3
10	CxHy	0-1%

it is noted that methane and carbon dioxide is the main constituent of biogas, and its composition generally varies between 25 to 80% based on the quality of the feedstock and process control. Other constituents of biogas are Nitrogen, hydrogen, and hydrogen sulphide. 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[20]. Additionally, the composition of the substrate and process conditions influence the concentration of methane and carbon dioxide and hence overall composition of the biogas produced from the substrate[53]. 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 steady and optimum generation of biogas[19, 20, 54].

F. Biogas Plant Processes

In a biogas plant, organic waste or substrate is fed into the hydrolysis tank where proper 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 then fed to the anaerobic tank for digestion[48, 49]. In methane formation, different bacterial/archaea communities operate in a syntrophic relationship. In hydrolysis stage complex carbohydrates, fats, and proteins are first hydrolyzed to their monomeric forms by action of exoenzymes and bacterial cellulosome. During acidogenesis that follows, the monomers formed in hydrolysis are degraded into short-chain acids which include acetic acid, butyric acid, isobutyric acid, valeric acid, propionic acid, isovaleric acid, caprionic acid, hydrogen (H2), alcohols, and carbon dioxide (CO2) During acetogenesis, these short-chain acids are converted into acetate, hydrogen, and carbon dioxide. It is the methanogens then that convert the intermediates produced into methane and carbon dioxide. Studies show that about 1/3 of methane formation is a result of reduction of carbon dioxide by hydrogen[21]. The chemical process is illustrated in figure 2.

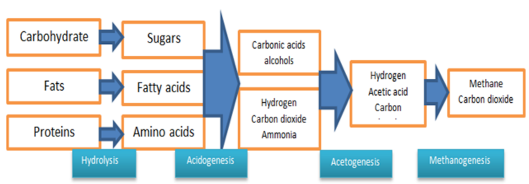

Fig. 2. Processes that lead to biogas production[55, 56]

From figure 2, it is noted that the anaerobic digestion process is divided into four main processes. They are hydrolysis, acidogenesis, acidogenesis and methanogenesis. The process starts with hydrolysis where the fats, proteins and carbohydrates are converted to fatty acids amino acids and sugars. This followed by acidogenesis they products of hydrolysis are converted to carbonic acids, alcohols, hydrogen, carbon dioxide and ammonia. The products of acidogenesis are subjected to acetogenesis to form hydrogen, acetic acid, and carbon as the main products. These three products are further broken down through methanogenesis process to form methane and carbon dioxide, which are the main components of biogas. The organic matter used for biogas production should contain easily biodegradable matter to speed up the process of hydrolysis. Most bacteria operate at a pH level range of 6.8-7.3 which are close to neutral conditions. Maintenance pH level of about 7.0 can be achieved by addition of calcium hydroxide. Another important parameter is the C/N ratio which should vary between 15-25 for optimum biodigestion. Substances which may inhibit the process and hence should be controlled or avoided include detergents, antibiotics, antiseptics, ammonia, volatile acids, and heavy metals. The Solid to moisture ratio which is another important parameter in bio-digestion should be high enough but should not lead to huge requirement of digestion space[31, 57, 58]. The hydraulic retention time (HRT) which is the average time in which the sublayer for anaerobic digestion process is retained in the digester, in contact with biomass (bacterial mass) is another important parameter influencing biogas production[51, 59]. Although a shorter hydraulic retention time produces a good rate of the raw material flux, the overall biogas productivity is reduced[3]. On the other hand, a longer hydraulic retention time requires a higher reactor volume and consequently additional cost of installation, operation, and maintenance. This implies that there is need to establish an optimum HRT for the substrate. The HRT is determined based on digester volume and the substrate loading rate. 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[57]. The recommended maximum height of substrate in a digester should not exceed 3.5 m or pressure of 34.33 kPa and hence horizontal flow digesters are preferred[46].

G. Slaughterhouse Waste

Abattoirs produce large quantities of biodegradable waste that can be used for biogas production[13]. Slaughterhouse waste has similar chemical properties with municipal sewage; but it has a higher concentration of solids than wastewater with about 45% dissolved solids and 55% suspended solids in the composition [60]. Of the constituent components, blood has a very high COD of around 375,000 mg/L(milligram per liter) and is one of the major dissolved pollutants in slaughterhouse wastewater[60]. Wastewater from slaughterhouses has high COD of 3,000 to 30,000 mg/Liter, fats, oil, and grease (FOG) of about 375 mg/L, suspended solids of 872 + or - 178 mg/L, nitrogen 186 +or -27 mg/L, total phosphate 76= or-36 mg/L. However, the composition varies widely from one slaughter to another[12]. In a study by[41] on material and energy recovery from a poultry slaughterhouse, in South Korea, the intestine residues have the highest content at 28.96% of the waste and also accounts for 65.8% of the total Nitrogen generated in the facility at the rate of 22.46 kg per 1,000 heads of poultry per day. Phosphate (P2O5) generation stood at 0.194 kg per 1000 heads of poultry a day, while potassium (K2O) generation stood at 0.459 kg per 1,000 heads of poultry per day. Methane recovery rate in form of CH_4 stood at 35 Nm^3 per 1,000 heads of poultry per day of which 88.1% although the study further showed a prolonged lag period of 33.7 days in a batch biogas digestor. This shows that poultry slaughterhouses have a potential not only to supply energy as biogas, but also important farm nutrients for the soil mainly nitrogen, phosphorus, and potassium.

H. Biogas Production from Slaughterhouse Waste

Meat processing generates huge quantities of wastes made of FOGs, blood, paunch, and manure. Biodegradation will reduce BOD, COD, FOGs and total suspended solids[61]. For optimum biogas production from slaughterhouse waste, the waste mixture should have higher proportions of stomach and intestines wastes and less blood. This is because blood has got high content of Nitrogen which may inhibit biogas production [13]. Anaerobic digestion is said to be optimum if acid formation phase which consists of hydrolysis and acidogenesis and the methane production phase consisting of acetogenesis and methanogenesis take place simultaneously in dynamic equilibrium [17]. It is difficult to maintain anaerobic process stability due to presence of high microbial populations. In biogas production, the biosystem is prone to upset due to shock loads or temperature fluctuations during operation[18]. So the design of an anaerobic digestor to function optimally, it must be based on the limiting characteristics of these microorganisms[61].

H.1. Energy Potential of Slaughterhouse waste

A homogeneous mixture is critical requirement for optimum biogas production from slaughterhouse waste, which is characterized by existence of large solid particles, separated waste streams, and high level of heterogeneity which are not conducive for anaerobic digestion. Maceration is often necessary by use of a heavy-duty grinder for bulk reduction and creation of homogeneous mixture of feedstock. A typical example of a macerator operates at 1200 kg/h and has electricity demand of 7.5 kWh or 6.25 kWh/ton of feedstock[43]. Several studies on biomethane potential of animal waste shows that poultry slaughterhouse generates methane of up to 610 ml/g of volatile solids from intestinal waste, while the feathers generate 200 ml/g of volatile solids under mesophilic conditions. For bio digestion under thermophilic conditions, methane generation from intestinal wastes is about 675 ml/g of volatile solids and about 276 ml/g volatile solids for poultry feathers. The studies further show that addition of zeolite reduces chemical oxygen demand for up to 57% while volatile solids reduction increased from 13 to 19%. The ammonia –nitrogen concentrations can be decreased by 15.5 mg/l because of application of zeolite. The studies also showed enhanced biogas production of 700 ml/g volatile solids after 25 days because of zeolite addition. Therefore biogas generation under thermophilic conditions increases biogas production compared to mesophilic conditions for slaughterhouse waste while control or reduction of ammonia by zeolite additions also significantly increases biogas production from chicken slaughterhouse waste[62]. In a practical case of industrial scale biogas production from slaughterhouse waste, studies at St. Martin biogas plant in Upper Austria showed the significant potential of biogas production with very important lessons for future development of slaughterhouse waste to biogas conversion schemes[63]. The ban of rendered products from the food chain by the European Union in 1999 led to significant increase in slaughterhouse waste and hence the cost of waste disposal which triggered the demand for anaerobic digestion as an economical means of slaughterhouse waste disposal buy the slaughterhouse[64]. The then capacity of the slaughterhouse was 550,000 pigs and 50,000 cattle per year with two slaughtering facilities. This shows that most of the slaughterhouse came from the pig slaughtering facility and this influenced the location of the biogas digestor between the two facilities that are 5 km apart[2]. The initial status of the slaughterhouse before development of a biogas plant was that it had energy demand of 5.5 to 7.0 GWh of electricity derived from the electricity grid and 4.5 to 6.0 GWh of heat produced in a natural gas and compressed natural gas fired boiler. The total waste generation was 13,700 tons annually inform of pig intestinal content being risk 2 material and blood, grease separation material being risk 3 materials. Additionally, the pig slaughterhouse produced 3,500 tons per year in form bones, skin, head, and eyes which were sold to the existing market hence no need for treatment as waste. The 13,700 tons were disposed by rendering at a facility located 80 km away costing 25,000 to 30,000 liters of gasoline for trucks whose carbon equivalence was 80,000 and 96,000 kg of CO2 per year[2]. The annual freshwater demand by the pig facility was about 86,000 tons and, in the process, accumulating about 4,200 tons of grease sludge for discharge to the local wastewater treatment plant[2, 64]. To solve the challenge of waste disposal when rendering was banned, the company was the first one globally to establish a biogas plant that exclusively uses slaughterhouse waste as substrate for biogas production[65]. Total waste consisted of about 10,000 tons of blood, rumen content, colon content and waste from grease separation. The slaughterhouse waste was used to produce 3.6 million kWh of electric power and 3.6 million kWh of thermal energy year[65]. The biogas plant was meant to reduce the cost of waste disposal which had increased greatly, while at the same time producing energy for own use as heat and electricity. The company was using natural gas and imported grid electricity to meet its energy requirements[8],[64],[65]. The project upon implementation reduced the disposal costs and met about 33% of its electricity demand in addition to 75% of the process heat energy demand with renewable energy [32]. The specifications of the biogas plant are summarized in table 5 below.

Table 5. Grossfurtner biogas plant specifications [65]

	Parameter	Specifications
1	Biogas output	5,000 m3/day
2	Methane content	67% - 69%
3	Installed electricity & heat capacity	525 kW electric, 525 kWh thermal
4	Digester's capacity	2600 m3 (1x600m3, 2x 1000m3
5	Substrate	2000 m3 blood, 1,000 tons rumen content, 3,000 tons colon content, 4,000 tons grease separation material
6	Substrate loading	170-230 tons/week
7	Pretreatment used	Continuous pasteurization.
8	Operating hours/availability	8,400 hrs./year (95.9%)
9	Electricity feed in tariff rate	11 cents/kWh
11	Sale tariff (Heat/thermal)	Heat is for internal use
12	Waste Disposal cost	5-50 €/ton slaughterhouse waste
13	Total investment cost	€1.8 million for the first phase in the year 2003

Table 5 show that specifications for the biogas plant at Grossfurtner slaughterhouse in Austria. It is noted that the first phase of the project costed € 1.8 million in 2003. Electricity is exported at a price of 11 cents per kWh implying that the slaughterhouse gets extra revenue from the sale of excess power. The availability of the plant is 95.9% which shows that it records low levels of shutdowns. With the biogas facility supplying biogas to the combined heat and power facility, about 85% of the waste generated could be converted to energy to 2,700 MWh thermal and 3,200 MWh electrical energy with thermal energy used in the heating processes. The initial annual cost savings in energy and waste disposal costs were about 63% with computer payback period of 9 years. In addition to cost savings, the biogas-based CHP facility led to the positive environmental impact with 79% reduction of greenhouse gas emissions i.e. from 4.5 Million kg CO2 to 0.9 Million kg CO2 per annum[2]. Biogas produced from anaerobic digestion of slaughterhouse waste can be put to various energy applications like direct combustion, combined heat, and power (CHP) and biomethane production for injection to the gas mains. It is possible to meet the entire electrical and heat demand of slaughterhouses by a CHP system which can have overall electrical efficiency of 41% and thermal efficiency of 49%. Electricity produced can supply the entire electric power demand of biogas production excess for external use or export[43].

H.2. Factors influencing Biogas Production from Slaughterhouse waste

Slaughterhouse waste has got high fat and protein content which increases their Biomethane potential (BMP). On the other hand, fats exhibit low surface area and lower solubility which is a challenge to bacterial action[66]. Slaughterhouse waste is also characterized by existed large particles in the feedstock which limits biogas production potential[43, 66]. Slaughterhouse has good methane potential producing 225–619 dm^3/kg corresponding to 50–100% of theoretical yields. A study in which thermophilic batch digestion of pig slaughterhouse waste of category 3 was done yielded 1.67 m^3kg-1 VS which corresponds 1085 dm^3/kg based on methane concentration of 65% which is very high and corresponds to theoretical yield values for lipids. A study where mesophilic fed-batch digestion was done with mixed, minced animal by-products yielded 760 dm^3kg-1 VS or about 490 dm^3kg-1 VS for untreated waste as feed stock which is lower compared to the 619 dm^3kg-1 VS for mixed pork feedstock realized in batch assays[42]. Therefore, waste treatment and type of the feedstock are important factors in biogas production from slaughterhouse waste. Feedstock dilution is another important factor influencing biogas yield in bio digestion. For most slaughterhouse by-products, specific yield of methane is highest when the animal by-products were at the highest dilutions of about 5%. Animal waste substrates with highest content of lipids, and proteins makes them prone to cause inhibition unless they are diluted. The N-concentration is another important factor with studies showing that where total-N concentrations were higher than 7 g of N/ kg, the biogas production e process was severely inhibited hence limits methane yield[42]. Therefore, dilution is an important factor in biogas production as it limits its concentration of process inhibiting agents. Therefore, from literature it is noted that slaughterhouse or animal waste is a very good substrate for methane production with a methane potential for mixed animal waste of about 619 dm^3kg-1, which is higher than feedstock like manure that yields 20–30 dm^3kg-1 under similar conditions. The main challenge with slaughterhouse waste is management of high ammonia loads, associated with thermophilic digestion of slaughterhouse waste. Therefore, mesophilic digestion is recommended for slaughterhouse waste anaerobic digestion. Additionally, co-digestion is recommended but with a dilution level of 5%. It is also necessary to carry out waste pretreatment to meet environmental regulations as has no significant effect on treatability or methane yield of the slaughterhouse waste[42]. Waste from slaughterhouses residues have approved to be attractive substrates for biogas production mainly due to high cost of disposal and increasing need for renewable energy sources[17]. Investment in slaughterhouse waste to biogas has potential to reduce disposal costs, ensure a clean environment and meet the entire energy needs of slaughterhouse facilities with excess for export to the grid as electricity [41]. One other limitation of slaughterhouse waste is fractions like blood which have high nitrogen content which produces ammonia that inhibits microbiological action in biogas production. To minimize ammonia content, slaughterhouse wastes generally are used with co-substrate to limit ammonia content to maximum 5 g/l in the digester content[20]. 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[13]. Theoretically the proteins generate biogas with 68% methane, while the lipids generate biogas with 72% methane. Several practical limitations limit the digestion of slaughterhouse waste. The main limitations being slow hydrolysis rate of some materials, foaming and floatation which is caused by lipid digestion. This factors combine to lead process disturbance and inhibition by certain intermediates like long chain fatty acids (LCFA), hydrogen sulfide (H_2S) or ammonia (NH3), formed during anaerobic degradation[2, 64]. Different animal products and parts exhibit different biogas potential as summarized in table 6 below.

Table 6. Methane potential of several slaughterhouse substrate material [33]

	Substrate Type	Methane potential (CH4/kg of DOM)
1	Rumen content	300
2	Rumen press water	280
3	Screenings	650
4	Grease trap residues	710
5	Flotation tailings	700
6	Municipal sewage sludge	330

Where DOM is dry organic matter Table 6 above shows that different materials of the slaughterhouse waste in substrate have different methane or biogas potential. The potential yield is compared with municipal sewage sludge whose potential is 330 CH_4/kg of DOM as compared to flotation tailing whose yield is 700 CH_4/kg of DOM. Others are grease trap residues screenings, rumen press water and rumen content whose potentials are 710, 650, 280 and 300 respectively. Therefore, the list potential is obtained from rumen waste and rumen press water[33].

I. Biodigester Design and Operation

Biogas digestors are important components as they are used in biogas digestion which leads to production of energy rich biogas, nutrient rich digestate and waste reduction[21]. The design of most biogas plant systems is based on the China Fixed Dome (CFD) with over 6 million units in use, India Floating Cover (IFC) with over 2.9 million units in use or designs that combine features of the two basic designs[67]. The fixed dome digestors or hydraulic digestors biogas plant is the most popular because it is more durable and has less maintenance requirements. The digestors are filled by means of inlet pipe to the bottom level of expansion chamber[21]. However, the fixed dome digestor needs more care and precision in design and construction[68]. Digestors have life time of 25 to 35 years while costs vary generally between 200 and 400 US dollars[21]. The biogas plant consists of three min parts namely the mixing chamber, the digestor and the expansion chamber. The mixing chamber is where feedstock is mixed with water before feeding the digestor. The digestor is the chamber where anaerobic digestion takes place leading to biogas production and the formation of sludge or digestate. The expansion chamber is the space where excess slurry flows to via overflow pipes whenever the digestor is congested. The congestion could be due to gas accumulation in the chamber[68]. Materials used in digestor construction may vary with geographical location, hydrology, local conditions, cost, and availability of construction materials. Materials used include brick, mortar, cement, plastics, steel, and stones[21].

I.1. Digestor sizing

Digestor sizes involves determining the optimum size of the biogas plant to be constructed based on several factors. The size is mainly determined by amount of feedstock, energy demand, and affordability of the plant in terms of cost of the plant and available capital. Oversizing of the plant is not recommended as it leads to underfeeding hence low gas production with low pressure that may not be sufficient to displace the slurry from the chamber leading to slurry buildup and congestion of the digestor. In fixed dome biodigesters, the real and active volume should be to the level reserved for gas storage above the digestion space. The average digester volume VD is a function of the Radius, and the volume of the expansion chamber is equal to the volume of the gas storage space. To keep gas pressure below 1.3 m of water column (12.753 kPa), the depth of expansion chamber is kept at 0.5 m and gas storage capacity should not exceed maximum VG[68].

I.2. Inlet Chamber design

The role of the inlet chamber is to provide space for proper mixing of feedstock and water before the mixture is fed to the digestor. The inlet chamber or mixing chamber may or may not be built with a mixing device, but effort should be made to ensure that it is possible to improve the quality of substrate for digestion to achieve optimum biogas production. The mixer when installed should be firmly attached to the structure, be easy to operate and maintain easy to operate for effective feedstock/substrate mixing process while the metal or steel parts in contact with the substrate should be galvanized or be made of non-corroding and non-reactive materials[17, 20, 28]. The mixing chamber bottom of floor should at least be at least 25 cm above the outlet overflow position. The chamber should be designed for easy operation when mechanical mode malfunctions and hence the need for manual[68].

I.3. Expansion chamber

The expansion chamber should be designed and drawn in line with design principles and guidelines before construction at the correct location in the biogas plant next to the biodigester. The size of the expansion chamber is directly related to the volume of the gasholder for proper operation of the biogas plant. The outlet floor and walls should be accurately located and positioned in the design. The walls should be smoothly finished with a layer of cement and plaster. The wall should be sufficiently reinforced to the overflow level. The positioning and level of expansion tank should be such that it is on a slightly higher elevation compared to surrounding to prevent rainwater from going into the outlet during the rainy season. The dome construction, the concrete base for the expansion chamber ought to be caste. For the purpose of strength, the slab for the top opening should be properly reinforced[68].

I.4. Dome Construction

A biodigester dome is built above the round wall and should be strong enough to contain own weight and pressure of produced gases. Construction should be carefully done around the top of the biodigester wall resulting in a dome shaped structure above the digestion space. Where bricks are used, they should be placed as close as possible with a strong bond before the spaces between the brickwork are filled with mortar. Important in design and construction is to avoid cracking and collapse of the structure[68].

J. Critical Review

Slaughterhouse waste is significant especially in urban areas where environmental challenges are many. Although many options are available for disposal of slaughterhouse waste like alkaline hydration, composting, rendering and anaerobic digestion, biogas production alongside waste treatment and organic fertilizer production and its high potential of pathogenic sterilization or inactivation makes anaerobic digestion a very attractive option for slaughterhouse waste disposal within the framework of global sustainable energy transition and development. Literature shows significant potential of biogas as a raw material for biogas production and an option as a better means of waste disposal although a study on St Martin showed 63% as overall efficiency of the biogas plant. This study investigates the performance of Nyongara slaughterhouse biogas plant with the view of identifying challenges and proposing solutions. Biogas as a source of energy remains cheaper and reliable source of energy although it has experienced several obstacles in its development and use. The following factors stand out to have affected the development and use of biogas; high costs of installing the systems, systems failures, Inadequate or lack of post installation support, poor management, and maintenance, Inadequate or lack of technology awareness, Scarce and fragmented promotional activity, and Standards a major issue currently facing the sector. Similarly, there are more potential areas which need to be promoted in enhancing biogas technology like in slaughterhouses, schools, colleges, prisons, slaughterhouses, and restaurants. The governments in question should initiate the process through sensitization and provision of necessary facilities and finances. Although a lot of research has been carried out on biogas production and application, this study is unique as at views biogas production from an environmental and socioeconomic point of view at a time when the world is looking for practical measures to combat greenhouse gas emissions and looming global warming in a sustainable manner.

3. MATERIALS AND METHOD

This study reviews the potential of heat and power generation from slaughterhouse waste and measures to improve operating abattoirs as part of the global transition to a green and low carbon grid electricity systems and clean environments for sustainable development. The study targets an operating biogas plant in a slaughterhouse at Dagoreti in Nairobi Kenya which is located about 26km away from Nairobi. Data collection process started with a visit to the facility for familiarization and hence development of an effective research design. 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 was necessary for performance analysis and redesign of the biogas plant. Primary data was collected through observation and document analysis as well interview and questionnaire concerning the operation and design of the facility. Secondary data was collected from available published literature on the Nyongara slaughterhouse and was used as background and reference data to guide the investigation. Official permission was sought from the slaughterhouse management to let the research and data collection be carried at the plant[47]. Data had to be analyzed and presented using descriptive statistics[69]-[71]. The data collected at Nyongara slaughterhouse were tabulated thoroughly checked for accuracy and completeness. The outcome of the comparison was discussed, and conclusions made based on the results and discussion. The conclusions drawn were then used to make recommendations to the Nyongara slaughterhouse management and make suggestion what other researchers can do further[47, 48].

A. Target Population and Authority

In this study, the target population for data collection is respondents who possesses the information sought for by a researcher to support the study and hence are the workers, management and owners or directors. Official request for authority was made to the management of the facility who gave consent

B. Sample Size

Sampling is an important process in research because it is often not possible to gather data from all the relevant members within a population. For the purposes of selecting respondents a sampling procedure was deemed necessary for this study. The current research required that non-probability sampling approaches be used and in particular purposive sampling. Purposive sampling is meant for a particular purpose, where people are chosen who are relevant to the research topic and who the researcher believes can provide the best information to achieve the objectives of the study. For effective exercise, the reserachers ensured that the size of the sample was neither too large nor too small. An optimal sample was selected for this study based on access and availability of the respondents. An optimal sample is one which fulfils the requirements of efficiency, representativeness, reliability and flexibility. The sample size for this study consisted of 3 categories of people i.e. the slaughter house management and the biogas plant oerators and slaughterhouse operation personnel.

C. Sampling technique

Sampling is the process of selecting elements from a population in such a way that the elements selected represent the entire population. It is a statistical practice concerned with the selection of individuals intended to yield some knowledge about a population of interest. Sampling is useful in research because one learns some Information about a group by studying a few of its members thus saving time and money. This research required that non-probability sampling approaches be used and in particular purposive sampling. Purposive sampling is meant for a particular purpose, where people are chosen who are relevant to the research topic and who the researcher believes can provide the best information to achieve the objectives of the study.

D. Data Analysis

The data collected at Nyongara slaughter house were thouroughly checked and compared with parallel or alternative sources for accuracy and reliability, then summarised, tabulated and analysed. 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. Recommendations were done in line with our objectives of the study.

E. Data Collection Instruments

In this research both primary and secondary data were instrumental in provision of data needed for this research. Primary data was collected through observation of the biogas plant design, manuals, and structured personal interviews with the manager of the slaughterhouse and two workers at the biogas plant. Secondary data was collected through desktop research and review of relevant literature and peer reviewed publications on the facility, as well as documents and past records available at the slaughterhouse.

i.) Observation

Nonparticipant observation technique was used to gather information on the general layout, cleanliness, material flow and handling and physical environmental factors. Photos were taken of selected areas of the facility for use in the research. Important parameters observed included temperature, nameplate specifications on plant and equipment, this data collection method involved watching and recording the process parameters. This gave a clear picture of the status of the biogas plant.

ii.) Document review

Data was collected from of written records, reports on the plant operation and maintenance plant equipment manuals were accessed to gather information needed for performance analysis and reports on design, operations, and maintenance. The plant design manuals and drawings were availed to for review and technical details like specifications including materials and dimensions were provided from these documents.

iii.) Interview

The interview targeted all available and accessible workers at the facility due to their limited number. Oral requests were made to respondents who were interviewed through face-to-face question and answer approach. All the plant employees accepted to be interviewed and provided important information based on their practical experience like operational challenges and opportunities, type breakdowns and how they correct them and performance of the digestor. The interview was conducted without limiting the respondent's scope of knowledge on biogas production technology; therefore, questions were asked in a progressive manner where one question and answer led to another one. However, the main data sought is summarized in figure 3.

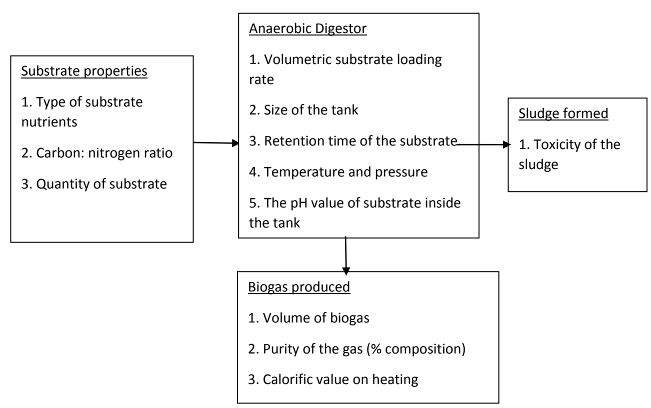

Fig. 3. Data collected.

From figure 3, it is noted that data sought by researchers was about the design, process, parameter snad outputs i.e. substrate and substrate properties, the digestor and anerobic digestion process, the digestate or sludge and biogas produced in teerms of productivity, properties process.

F. Limiting Conditions

This study encountered a number of limitations which may have affected data collection leading to a biased analysis and conclusions on the performance of the biogas plant. Most of data collected was gathered by means of interview and observations and hence needed verification from credible sources like official documents and manual which were not accessible in some cases. Very limited and little data could be secured from published and other official sources like government reports. The number of respondends available for data collection were also few in number making application of sampling techniques difficult. From the small population. An accurate facility performance analysis was not also possible due to lack or complete data on daily production, poor facility instrumentation and limited reporting arrangements and requirements. However, the researchers collected as much data as possible that made the research successful.

G. Validity and Reliability of of Data

The respondents were asked similar questions as a means of checking reliability of data. Information provided through interview and questionnaire was compared with documented data for accuracy verification. Technical data on nameplates and equipment operating manuals was compared for accuracy for data like plant equipment capacity and specifications.

H. Data Analysis

The collected data was analyzed and presented using descriptive statistics with results being used in the design of a better biogas plant for the Nyongara slaughterhouse.

H.1. Plant Description

The Nyongara biogas plant is equipped with a modern structure for biogas production from the slaughterhouse with the biogas being used as a fuel to an existing 10 kW biogas engine generator. The main challenge facing the facility is low capacity based on available biodegradable slaughterhouse waste [10]. Excess effluent mainly consisting of blood and fecal matter is channeled to Kabuthi River, which is a tributary of Nairobi River, threatening millions of the residents of Nairobi with water borne diseases and polluted environment as the river passes right at the city center. The facility was closed for six months in 2009 by the National Environment Management Authority (NEMA) for contravening the existing environmental regulations[20]. The closure of the slaughterhouse on account of environmental pollution forced the management to develop the biogas plant to reduce the environmental impact and, in the process, generate own energy. This biogas initiative and project brought together several public and private sector institutions including Kenya Industrial Research and Development Institute (KIRDI), The United Nations Environmental Programme (UNEP) and United Nations Industrial Development Organization (UNIDO) and in 2009, who partnered to launch the pilot project. The biogas plant project of the Nyongara slaughterhouse facility became operational in the year 2010[10].

H.2. Specifications of Existing Facility:

The existing biogas plant has the following specifications: 3.5 m^3 hydrolysis tank, 60.0 m^3 anaerobic digester bag and 7.0 m^3 overflow tank. The hydraulic retention time is 17 days and the average amount of biogas produced daily is 35.0 m^3. The performance of the biogas plant is influenced by the design of the biogas plant, process design and control system, the level of instrumentation, type of organic matter in the substrate including the mixing ratio, the operating temperature and pressure in the digester, pH value of the substrate. These are the main factors investigated in this research. Optimization of these factors could help increase the amount of biogas produced thus reducing fuel costs as well as environmental pollution by the slaughterhouse waste[72, 73]. The biogas facility is illustrated in figure 4.

Figure 4 is the front view showing the hydrolysis tank of size 3.5 m^3, sludge treatment tanks for preparation of substrate, 60 m^3 digestor, the digestor house storing a 40 m^3 gas storage bag and solar panels on the roof for water which is stored in hot water tanks installed above the roof.

Fig. 4. Biogas plant at Nyongara (photo by Authors)

Fig. 5. Hydrolysis, digester, overflow, and treatment tanks (Photographed by researcher)

Figure 5 shows the overflow tank, hydrolysis tank and the digestor in the biogas plant made of concrete material. The main elements of the digestor are made of concrete as the building material.

H.3. Organic waste from the slaughterhouse

Data from the slaughterhouse records showed that, 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 Kshs 30,000 monthly [20]. 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 study at Nyongara slaughterhouse showed that solid waste amounts to 16,000 kg alongside 40 m3 of liquid waste daily. Kshs 100,000 was spent monthly on solid waste disposal [74, 75]. The liquid waste was 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.

This study showed that at Nyongara 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 300 kg/m^3 while that of slaughterhouse wastewater is 1,000 kg/m^3[32].The waste generated from the four slaughtering units daily was determined as follows in table 7.

From table 7 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 7. Table 8: Composition of organic waste fed into the digester [20].

From table 8, 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 0.16 m^3, then the 300 kg solid waste from the Nyongara Slaughterhouse should be expected to produce the following volume of biogas daily. For the 300 kg of solid waste, biogas capacity is estimated at 48 m^3 of biogas daily[20, 26, 28]. This implies that the expected volume of biogas produced at the Nyongara slaughterhouse biogas plant for the 300 kg solid waste fed daily is 48 m^3. The solid waste to liquid waste ratio at Nyongara slaughterhouse is 300 kg solid waste: 2.5 m^3 of liquid waste. Therefore, if all the solid waste amounting to 16,000 kg was fed to the digester, using the ratio stated above, the total liquid waste to be used should be: Liquid waste = 16,000 kg / (300 kg / 2.5 m^3) = 133.33 m^3. This means that all the 40 m3 would be used and an additional 93.33 m^3 needed to ensure the volumetric mixing ratio is maintained. If 300 kg = 48 m^3 of biogas 16,000 kg =? Y x 300 kg = 16,000 kg x 48 m^3 hence, Y = 2,560 m^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 3.5 m^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 (2 days) to break down to smaller particles. One of the tanks is opened daily to discharge 3.5 m^3 into the digester, and then fed with fresh substrate. The next discharge from the tank is after 48 hours.

ii.) The digester design and performance: This is an airtight 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 biodigester are shown in table 9.

From table 9, 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 60 m^3. The hydraulic retention time (HRT) can be calculated as follows. Retention time = volumetric capacity of the digester / feeding rate = 60 m^3 / (3.5 m^3 / day) = 7 days The recommended maximum height of the substrate in the digester is 3.5 m. In contrary, the Nyongara slaughterhouse substrate height goes up to 4.0 m. This implies that the bacteria at the depth of 4.0 m experience a pressure of 39.4 kPa which is higher than the maximum of 34.33 kPa. This is demonstrated below. Pressure due to substrate height =$\rho g h$, where ρ is density of mixture assumed to be same as water density, g is the gravitational attraction and h, is the height of the mixture 4 m x 1,000 kg/m^3 x 9.81 m/s^2 = 39,240 Pa This pressure exceeds the threshold height of 3.5 m (34.34 kPa). The pressure is computed below. Pressure at 3.5 m = (3.5 m x 1,000 kg x 9.81 m/s2) Pa = 34,335 Pa. This implies that the substrate between the heights 3.5-4 m does not produce biogas at all, meaning that 0.5 m height of substrate goes to waste in every complete retention time. This wasted volume is calculated as shown below. Volume = Area x Height = 0.5 m x 3 m x 5 m = 7.5 m^3. Therefore, it can be noted that 7.5 m^3 of the digestor space does not contribute to biogas production as the volume is classified as high-pressure zone with respect to biogas production. 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. Because of lack of insulation and inadequate heating, the substrate temperature also reduces. Solar panels are used to heat and supply hot water for process heating and cleaning. The heating is however inadequate, and the temperature does not reach the optimum recommended temperature of 37 °C. This lowers the biogas activity and hence biogas production capacity. The plant is equipped with a biogas bag for gas storage. The main challenge is frequent bursting causing biogas loss which is undesirable to the environment in addition to the economic loss caused. The average pH level in the digester was established as 6.5, which is below the optimum 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.

H.4. Properties of biogas produced

The biogas produced daily is on average 40 m3. Table 10 provides a summary the average composition of the biogas produced. The gas produced is channeled to the gas storage room which houses a 40 m^3 gas storage bag. The calorific value of biogas can be estimated from the following physical and thermodynamic properties shown in table 10 below.

TABLE10

Table 10 shows that the calorific value of biogas is directly proportional to the percentage composition of methane in the mixture. The higher the composition of methane, the higher the calorific value of biogas. Computation of calorific value for biogas from Nyongara slaughterhouse can be done by interpolation. For the biogas at Nyongara, whose average methane composition is 65%, the calorific value can be obtained by interpolation demonstrated in table 11.

From table 11, it is noted that at zero degrees centigrade, calorific value for biogas with 64% methane is 5,479 kcal/m^3 while at 66% methane content, the calorific value is 5,650 kcal/m^3. Through interpolation of calorific values at zero degree centigrade, Caloric value of biogas with methane content of 65% at 0°C, is computed by interpolation, X0Oc = (66-65) / (66-64) x (5650-5479) + 5479 =5564.5 kcal/m^3 The calorific value

Table 7. 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)	16,000 kg	300 kg	1/88%
Liquid waste (Blood and wastewater)	40 m^3=40,000 kg	2.5 m^3=2,500 kg	6/25%
Total	56,000 kg	2,800 kg	5/00%

Table 8. Composition of organic waste fed into the digester [20]

Type of waste	Average bulk density	Amount fed to digester daily		% Composition	
Unit of measurement	kg/m3	Mass (kg)	Volume (m3)	Mass (%)	Volume (%)
Animal dung, intestine content, fats and rejected pieces of meat	300 kg/m3	300 kg	1 m3	10/57%	28/57%
Blood and wastewater	1000 kg/m3	2500 kg	2.5 m3	89/23%	71/43%
Total		280 0kg	3.5 m3	100%	100%
Mixing ratio					01:02/5

Table 9. Property/conditions of the existing digester bag

Property/conditions of the digester bag	Value
Volumetric capacity of the digester bag	60 m3
Height of the digester bag	4.0 m
Length of the digester bag	5.0 m
Width of the digester bag	3.0 m
Temperature	34^{o}C
Pressure	400 mm of water
The PH value	6/5
Feeding rate	3.5 m^3 per day
Volume of biogas produced	Average of 40 m^3 daily

Table 10. Calorific value of biogas [32, 56]

Methane content %	Calorific value at 0C and 760 mmHg, (kcal/m3)	Calorific value at 20C and 760 mmHg, (kcal/m3)
64	5,479	5,101
65	X0 0C	X20 oC
66	5,650	5,261

of biogas at with methane content of 65% at a temperature of 20 °C, X20oC = (66-65) / (66-64) x (5261-5101) + 5101 =5181 kcal/m^3 Petrol oil has a calorific value of 11,110 kcal/ kg,[20]. At 0°C the equivalence of petrol to biogas is given by. = (11,110 kcal/ kg) / (5564.5 kcal/m^3) =1.9966 m^3 of biogas / 1kg of petrol This can be interpreted to mean that the energy given by combustion of 1kg of petrol is equal to energy by 1.9966 m^3 of biogas at 273 K. Hence at 293 K the equivalence of petrol to biogas is given by. = (11,110 kcal/ kg) / (5181 kcal/m^3) =2.1444 m^3 of biogas / 1 kg of petrol This implies that the energy given buy combustion of 1kg of petrol is equal to energy by 2.1444 m^3 of biogas at 293 K. The heating value of combustible biogas generally with methane composition of 30% to 75% by volume, where the remainder is CO2. generally, varies in lower heating value/lower calorific value (LHV/LCV) of between 16 megajoules per cubic meter (MJ/m^3) and 28 MJ/m^3. Other than the use in electricity generation, biogas can be used for cooking and heating process water and other thermal applications in the slaughterhouse which will further reduce the energy bill and environmental impact[76]. The translates to about around 6 kWh/m3 of biogas. Biomethane which is enriched biogas hasa lower heating value (LHV) of about 36 MJ/m^3[77, 78]iomethane has similar properties with natural gas and can therefore substitute natural and can also be used by the slaughterhouse to run the biogas engine. Production of biomethane will require much more financial and technical investment[76].

H.5. Power Generation at Slaughterhouse

The biogas plant is equipped with a 10 kW three-phase ac 400V generator running on biogas. On average, this generator runs on biogas for 6 hours a day generally between 5:00-11:00 am to produce 10 kW electricity. The engine starts on petrol and once it is running but later changed over to biogas. Biogas is supplied to the engine by the suction power developed by the engine, 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[**?**]. Figure 6 shows the front view of biogas generator set used by the facility. Figure 6 shows the

Fig. 6. Front view of the biogas generator at Nyongara slaughterhouse (photo by researchers)

generator side of the biogas engine generator set at Nyongara slaughterhouse driven by the biogas powered engine to generate 10 kW electricity. Figure 7 shows the side view of the biogas engine set at Nyongara slaughterhouse.

Figure 7 shows a biogas engine generator set with gas pipelines and valves connected to the engine for biogas supply and operational control. Since 2.1444 m^3 of biogas is equivalent

Fig. 7. Side view of the biogas engine unit at Nyongara slaughterhouse (photo by researchers)

to 1 kg of petrol at 293 K[20], given the density of petrol = 719.7 kg/m^3, 1 kg of petrol = 1.389 liters. Hence 1.389 liters of petrol = 2.1444 m^3 of biogas. The amount of biogas produced daily is 35 m^3, based on the above relationship, biogas produced daily is equivalent 22.7 liters of petrol.

H.6. Measured Versus Optimum Conditions

The data shows that 300 kg of slaughterhouse waste is fed to the digestor daily. The measured digestion parameters are shown in table 12 against target or optimum conditions. The pressure recommended should not be more than an equivalent of 3.5 m of water while for thermophilic bacteria, average PH of 7. The maximum pressure = ρgh=1000x 3.5x 9.81 kPa=34.34 kPa. (Where, ρ is water density, g= gravitational force and h is maximum height of water[47, 48, 78]. Anerobic bacteria are generally classified as a based on optimum growth temperature. They are psycrophiles (> 20 °C), mesophiles (20–40 °C), and thermophiles (> 45 °C)[79]. The activity of the microorganisms roughly doubles for each 10 °C increase in temperature up to an optimum of about 37 °C for mesophilic bacteria[**?**].

From table 12, it is noted that the hydraulic residence time for the biogas plant is 17 days, average digestor temperature is 34 oC, average pH is 6.5, average height of substrate in the digestor is 4.0 m, volumetric mixing ratio is 2.5 and average biogas production is 35 m^3 per day. Based on the above comparisons shown in table 10, 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 56,000 kg yet only 2,800 kg 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 reduce environmental pollution. It can also be noted that biogas produced is 35 m^3 as opposed to 48 m^3 expected outputs, a deviation of -13 m^3. Therefore, the current biogas production stands at 72.9% of the expected output.

H.7. 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 300 kg/m^3 = 12,000 kg. This will increase solid wasted utilization from 1.875% to 12,000 kg / 16,000kg x 100% = 75%. The liquid to be utilized is 40 $m3$ which is 100% of the waste. With the mixing ratio of 1:1, the total volume of hydrolysis tanks is (40 + 40) = 80 m^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 3.18 m and height of 2 m.

ii)Digester: To attain the retention time of 20 days with a substrate feeding rate of 80m^3 /day, the digester capacity should be 80 m^3/day x 20 days = 1,600 m^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 3.5 m and radius of 12.06 m. The height of 3.5 m eliminates the need for stirring since methanogenic bacteria operate optimally between the depth ranges of 0-3.5 m.

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 80 m^3. We recommend a height of 2 m, length of 6.3 m and width of 6.3 m.

iv)Heating system in the digester: The digester has an inbuilt 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 80 m^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.

v)Proposed digester: To attain the retention time of 20 days with a substrate feeding rate of 80 m^3/day is recommended which requires the digestor volume to be as computed below. The digester capacity should be: 80 m^3/day x 20 days = 1,600 m^3 To achieve required insulation the digester construction material should be concrete which is relatively cheaper and easy to maintain compared to plastics and steel. The shape of the digester is to be cylindrical with a dome on top. The tank is of height 3.5 m and radius of 12.06 m or diameter of 2,412 mm as shown in figure 6 below. With height being limited to 3.5 m, the process eliminates or reduces the need for stirring since methanogenic bacteria operate optimally between the depth range of 0-3.5 m. This reduces operation and maintenance cost of the digestor and hence the whole process cost. Figure 8 shows the proposed digester

Figure 8 shows the proposed digestor with larger volume but reduced overall height of substrate space to eliminate high pressure zones from existing digestor for better performance and increased volume to increase slaughterhouse waste utilization by the biogas plant.

vi)Existing Heating system for the digestor: The heat required to maintain the reactor temperature within acceptable range of 35 to 40^{o}C (average of 38^{o}C) can be realized by preheating the feedstock to 70^{o}C during the process of pasteurization[43]. The existing digester has an in-built heating system comprising of coiled stainless-steel pipes mounted in the digester as shown in

Table 11. Comparison of measured values to optimum values [83]

Property/conditions	Measured value	Optimum value	Deviation from optimum value
Retention time	17 days	20 days	3 days
Temperature	34 C	37 C	3 C
PH value	6/5	7	0/5
Height of the substrate	4.0 m	3.5 m	0.5 m
Pressure	4.0 m of H2O (39.24 kPa)	3.5 m of H2O (34.34 kPa)	0.5 m of water
Biogas productivity (300 kg of substrate)	35 m3	48 m3	13 m3
Volumetric mixing ratio	01:02/5	01:01	

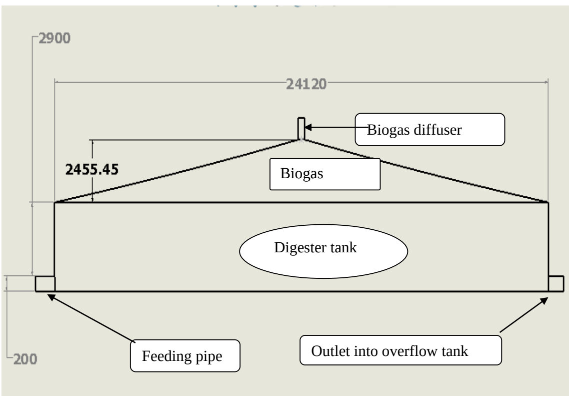

Fig. 8. Proposed digester (Authors conceptualization)

figure 7. Hot water at the inlet temperature of 95^{o}C is circulated through the pipes and exits the digester at 37^{o}C after heat exchange with the substrate. The substrate fed into the digester is 80 m^3 and is assumed to be at the atmospheric temperature of 23^{o}C. The working temperature in the digester required is 37^{o}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^{o}C to control the temperature not to rise or drop from the optimum temperature. Figure 9 below is an illustration of the existing heating system.

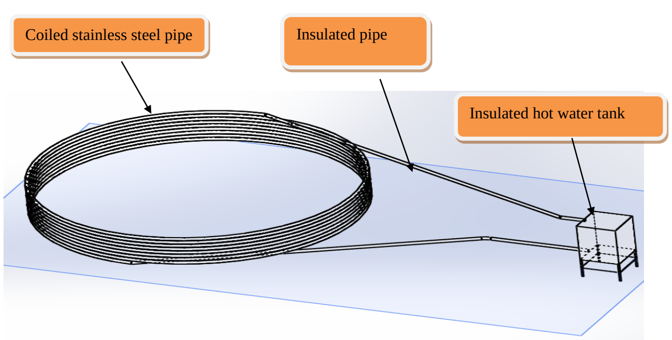

Fig. 9. Heating system (Author)

Figure 9 above shows the existing heating system for the biogas digestor, the main elements of the heating system are the coiled stainless-steel pipe, insulated pipe section and a hot water tank for storage of heating water. **vii.)Proposed heating system** The electricity demand for heating is generally 69.7 kWh/ton of water in feedstock while electricity demand for the biogas reactor is generally 10 kWh/ton of feedstock[**?**]. For analysis, the heat capacity of water will be used for substrate since water is used as a heating medium for the substrate and is also used as heating medium for proposed water heater. Heat gained by 80m^3substrate = Heat lost by the heating water = Mass x heat capacity x temperature change Taking density of substrate as 650 kg/m^3 then 80m^3 = 80 x 650 kg = 52,000 kg Temperature change= 37 °C - 23 °C = 14 °C = 14 K

Heat capacity = 4,200 J/kgK Heat to be gained by 80m^3substrate = 52,000 kg x 4,200 J/kgK x 14 K = 3.0576 x 109 J Heat lost by water to the 80 m^3 substrates = Mass x heat capacity x temperature change In the proposed heater, water heated to an average temperature of 95^{o}C is used. This will avoid boiling as steam is difficult to handle and is poor heat transfer medium. Temperature change = 95^{o}C – 37^{o}C = 58^{o}C = 58 K Heat capacity=4,200 J/kgK Mass of water =? Heat lost by water to the 80 m^3 substrates = Mass x (4,200 J/kgK x 58 K) = 3.0576 x 109 J Mass of water = (3.0576 x 109 J) / (4,200 J/kgK x 58 K) =12,551.724 kg Volume of hot water required in the pipes = (12,551.724 kg) / (1,000 kg/m^3) = 12,551,724 m^3 Length of the pipe to be coiled in the digester, L. Volume of water in the pipes = πr2 L = 12,551,724 m^3 Taking the radius of the pipe = 0.05 m, L= (12,551,724 m^3) / (0.052 π) =1,598.135 m The circumference of the digester tank = 2π r=2π 12.06 = 75.7752 m The estimated number of coils = (Length of the pipe) / (circumference of the digester tank) = 1,598.135m / 75.7752 m = 21 coils. Therefore, the proposed digestor heater will have 21 coils.

I. Digestor operating Conditions

For optimum performance, anaerobic digestion is influenced by several parameters. These parameters include the digestion or substrate pH, digestor temperature which influence bacteria activity, digestor substrate mixing, substrate characteristics including surface are or size, the C/N ratio of the feedstock, and HRT[21]. Whenever the substrate temperature is changed, the bacteria need a minimum of 3 weeks to adopt to new conditions hence the need to maintain steady optimum temperature in the digestor. There is a symbiotic relationship between hydrogen-producing acetogenic microorganisms and hydrogen-consuming methanogens during bio digestion that should be sustained. Neutral pH is preferred because most of the methanogens at a pH range of 6.7–7.5. Acid microorganisms prefer mesophilic conditions; while the methanogens, prefer higher temperatures. Substrate mixing is necessary for optimum biogas production although too much mixing causes stress to biogas producing microorganisms and create a favorable environment for undesirable foaming[20, 21, 84]. Optimum biogas production requires solid concentration of 5 to 10%. Higher solid concentrations significantly reduce biogas production[21].

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 below 6 and above 8 are restrictive to methane forming bacteria. This can be attained through addition of PH boosting reagents as shown in the table 13 below.

Table 12. Chemicals Commonly Used for Alkalinity Addition [85]

Chemical	Formula	Buffering Cations
Sodium bicarbonate	NaH2CO3	Na+
Potassium bicarbonate	KH2CO3	K+
Sodium carbonate (soda ash)	Na2CO3	Na+
Potassium carbonate	K2CO3	K+
Calcium carbonate (lime)	CaCO3	Ca2+
Calcium hydroxide (quick lime)	Ca(OH)2	Ca2+
Anhydrous ammonia (gas)	NH3	NH4+
Sodium nitrate	NaNO3	Na+

From table 13 above, it is noted that different chemicals can be used to increase the alkalinity. They include sodium bicarbonate and potassium bicarbonate are 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 heating supplied to the digester and the hydrolysis tank by means of coiled pipe network in contact with the substrate to increase the temperature. The hot water system should be fitted with a thermostat set at 37 °C to control the temperature not to rise or drop from the optimum temperature [86, 87]. Excess biogas can also be used to heat the substrate in addition to solar heating system. Water heaters can be designed and installed on the modified digestor to assist in maintaining the temperature within the optimum heating range.

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) = (1,600 m^3)/ (80 m^3/day) =20 days

4. RESULTS AND DISCUSSION

Slaughterhouse or animal wastes require cost-effective and safe method of disposal to reduce the risk of diseases and for additional economic benefits[39]. Various options are available for disposal or slaughterhouse waste. The various disposal systems are rendering composting, alkaline hydrolysis, anaerobic digestion, incineration and burning. Since slaughterhouse waste contains significant quantities of fats and proteins, they are an excellent substrate material for anaerobic digestion. Where the most important objective is inactivation of pathogens, then alkaline hydrolysis is the best option as it inactivates almost all pathogens in slaughterhouse waste[45]. Composting, alkaline hydrolysis and anaerobic digestion are discussed below. Various measures need to be put in place to increase the capacity of the digestor so that most of biodegradable slaughterhouse waste is digested as a solution to waste disposal. It is also important to optimize the digestion process conditions for more efficient and effective waste digestion and high productivity. To realize this, it is necessary to control the concentration of ammonia and nitrogen in the digestion as they inhibit biogas production. This can be realized by addition of chemical agents like zeolite that have proved to be effective in reducing the concentration of ammonia and nitrogen. However optimum conditions may need to be investigated to establish ideal conditions for optimum production with zeolite and other agents that reduce concentrations. Concerning the best thermal conditions for biogas production, this study showed that biogas generation under thermophilic conditions increases output compared to mesophilic conditions for slaughterhouse waste while control or reduction of ammonia by zeolite additions also significantly increases biogas production from chicken slaughterhouse waste From the data analysis, it is noted that 300 kg of slaughterhouse waste is fed to the biodigester daily producing an average of 35 m^3 of biogas. The parameters analyzed in the performance analysis which influence the digestor performance are the retention time of the substrate in the digester, the digestor temperature, the PH value of the substrate in the digestor, height of the substrate in the digester, pressure inside the digester. Based on the current throughput of 300 kg solid waste, expected biogas production per day is 48 m^3 unlike the current average of 35 m^3. This shows that the design and operation of the biogas plant needs to be optimized for greater biogas yield. The biogas plant on average generates 35 m^3 of biogas which is equivalent to 22.7 liters of petrol daily. The biogas productivity is reduced by operating parameter beyond the target or optimum values. This includes the PH of 6.5 instead of 7 which is not conducive for methane forming bacteria. A decrease in alkalinity is undesirable as it leads to an accumulation of organic acids due to the failure of methane-forming bacteria to convert the organic acids to methane. This leads to slug discharge of organic acids to the anaerobic digester which causes operation and maintenance challenges and poor-quality substrate and inhibits methane formation. The optimum temperature for the substrate is 37^{o}C which can be realized by heating the mixing water through solar heaters. Excess biogas can also be used for heating of the mixing water and substrate. Heating coils can also be designed to heat the substrate in the mixture to maintainer the digestor temperature at optimum temperature and hence increase bacterial activity and biogas production. The average height of the substrate in 4 m against a target value of 3.5 m which implies that the average digestor pressure is higher than recommended. The current design which allows substrate height of 4 m creates high pressure zones in the digestor that renders 7.5 m^3 of the digestor space not useful for biogas production due to high pressure which inhibits biogas production. The residence period of 17 days is lower than the recommended 20 days which implies that whereas the throughput of the waste is higher, biogas productivity is reduced and hence below optimum as an average of 35 m^3 is produced against optimum value of 48 m^3. With increase in volume to 80 m^3, residence time increase, high pressure zones are eliminated, and more production of biogas will be produced from the proposed digestor design. With the current digestor utilizing just 1.875% of available slaughterhouse, a simple analysis assuming similar conditions imply that the slaughterhouse has potential to produce 1,867 m^3 of biogas daily under prevailing conditions which is equivalent to 1,211 liters of petrol. Under optimized conditions as proposed by this study, the biogas plant can produce 1,660 liters of petrol per day from 52,000 kg of slaughterhouse waste. Based on this production, the slaughterhouse which generates 10 kW of power can generate more than 500 kW of power for own consumption and export to the electricity grid. This will help substitute power from fossil fuel sources while earning extra revenue for the slaughterhouse. The existing digestor performance parameters and indicators were noted and compared with optimal conditions with the objective of optimizing the digestor performance for maximum biogas production and waste digestion. The current values and target or proposed values are summarized in table 14 with deviation analysis.

From table 14 above, it is demonstrated that the biogas productivity increases in the new modified recommendation to 1,920 m3 from the initial 40 m^3. The plant material utilization is the measure of amount of bio digestible waste digested to the total waste available. The desire is to utilize all the available waste, but this cannot be realized because of low digestor capacity. The expected increase in utilization is attributed to the increase in size of the new plant that accommodates more waste. Solid waste utilization increases from 300 kg 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. In overall, the new proposal addresses major concerns and maximizes biogas production and minimizes environmental pollution effect by slaughterhouse. Slaughterhouse waste has significant potentials for generation of biogas and farm nutrients like phosphorus, nitrogen, and potassium. Biogas produced can be used to heat water for use in the slaughterhouse and as a fuel for biogas generators for electricity generation. Electricity produced then can substitute imported power with excess being sold to the grid to earn extra revenue for slaughterhouses. This is a working strategy for mitigating greenhouse gas emissions from fossil fuel sources in power generation. Biogas production from slaughterhouse waste is a function of treatment on the waste feedstock, the characteristics and composition of the feedstock, environmental and digestion parameters like feed rate, temperature, PH, and residence time, which are important for growth and maintenance of methanogenic bacteria. Therefore, maintaining enough methanogens is paramount to the overall performance of the system under optimum conditions.

5. CONCLUSION

Through various processes, slaughterhouses generate large quantities of wastes and wastewater in form of blood, urine, horns, hooves, eyes, paunch, among others which need to be disposed of safely, cost-effectively and in an environmentally benign manner. There are various methods available for slaughterhouse wastes with the cost of safe disposal of slaughterhouse waste having considerable increased primarily due to health concerns over the presence of pathogens in slaughterhouse wastes. Various methods of waste disposal are available with the selection being guided by cost, legislation, type of material and applications of the waste. Several different possibilities for their disposal exist and include rendering, composting, alkaline hydration, anaerobic digestion, and landfilling. This study established that Nyongara Biogas Plant produces an average of 35m^3 per day as opposed to the expected 48$m^3$for every 300 kg of solid slaughterhouse waste fed to the biodigester. This implies that the plant's biogas productivity at 72.9% of the optimum capacity. Out of the total solid and liquid waste of about 56,000 kg from the slaughterhouse, only 2,800 kg is utilized in biogas production leaving out 53, 200 kg of waste untreated by the biogas digestor. Therefore, that only 5% of the total waste is utilized in biogas production with 95% unutilized because of low capacity and efficiency of the existing biogas plant. The biogas plant does not fully realize the initial objective of self-reliance in energy production and environmental pollution control. On the positive note, it managed to reduce the electricity bill of the slaughterhouse by 66.7% and treatment of a small fraction of the generated and available biodegradable slaughterhouse waste from the facility. This research proposes the construction of an 80m3 capacity hydrolysis tank, 1,600 m^3 capacity digester tank and a 2,000 m^3 biogas storage bag for increased biogas production. Retention time would have to be increased to 20 days and substrate pH level increased to 7.0. The temperature must be increased to 37 °C. The sludge is passed to the treatment plant and can be safely disposed. These research shows that the proposed design and process modification of the biogas plant, will increased waste utilization by the biodigester from the current 2,800 kg to 52,000 kg which translates to 92.86% utilization. Due to high concentration of fats, foaming should be controlled by proper stirring in the new design. The high concentrations of ammonia and nitrogen that inhibit biogas production can be achieved by addition of agents like zeolite which have showed great potential to reduce ammonia and nitrogen. The environmental pollution by the slaughterhouse waste will be significantly reduced through anaerobic digestion while the slaughterhouse will be able to meet its entire energy needs and sell excess electricity and biogas for extra revenue for the facility. Biogas production is also increased from 35 m^3 to 1,920 m^3 hence reducing power cost for the slaughterhouse. This will contribute towards sustainable energy transition from reliance on fossil fuels to renewable energy and environmentally sustainable slaughterhouse operations which also generate fertilizer to sustain agricultural production. Therefore, slaughterhouse waste to energy conversion has huge potential control environmental pollution, generate extra revenue from sale of electricity, reduce production costs by avoiding electricity import and avoid greenhouse gas emissions through avoided generation of electricity supplied to the grid from the slaughterhouse. Therefore, slaughterhouses have a critical role to place in the energy transition through waste to energy pathways.

6. RECOMMENDATIONS

To increase biogas production and reduce the pollution effect, the Nyongara slaughterhouse management should adopt the proposed modification which will increase biogas production increase from the current 35 m3 to 1,920 m3. This will also see the solid wasted utilization increase from 1.875% to 75% and that of liquid waste from 6.25% to 100%. Further process and design modification is recommended to ensure all the biodegradable solid and liquid biogas waste digested in the biogas plant. This will control environmental pollution, generate excess electricity and biogas for export, fertilizer from the digestate and sustainable energy transition and slaughterhouse operations. This study concludes that design should maximize the total waste capacity utilization while operating digesters at optimum conditions will maximize biogas production and hence conversion efficient.

7. DISCLOSURES

A. Funding

There is no funding provided for this research and the whole exercise was fully funded the researchers.

B. Availability of data

The research has provided all data and information used and did not use any undeclared data and information. However, any datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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D. Ethics Approval and Consent to participate

Not applicable

E. Competing Interests

The authors have no financial or otherwise any conflict of interest.

F. Consent for publication

The authors have authority to publish the research work in any journal.

G. Author's contribution

The first author made the draft under guidance of the second author as academic advisor.

H. Acronyms and abbreviations

CHP: Combined heat and power; C/N: Carbon nitrogen ratio; DOM: Dry organic matter; GWh: Gigawatt-hour; HRT: Hydraulic retention time; kWh: kilowatt-hour, kJ: kilojoule; mg/g: milligram per gram of waste; K: degree Kelvin; kPa: kilopascal; Kshs: Kenya shillings; LCFA: long chain fatty acids; TWLK: Total live weight of animal killed; kcal: kilocalorie.

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