Optimum Bio-digester Design and Operations

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Abstract

Biogas is competitive, viable and generally sustainable energy resource due to abundant supply of cheap feedstock and availability of a wide range of biogas applications in heating, power generation, fuel, and raw material for further processing and production of sustainable chemicals including hydrogen and carbon dioxide and biofuels. The capacity of biogas power has been growing rapidly for the past decade with global biogas generation capacity increasing from 65 GW in 2010 to 120 GW in 2019 representing a 90% growth. The study showed that digester design, operation and maintenance is a very important aspect of biogas energy and technology development. It was established that there are three basic digester designs i.e. fixed dome, floating dome and fixed dome with expansion chamber. The main challenges facing digesters is silting, poor serviceability and limited mixing ability. Design improvements suggested are manual and motorised mixing and provision of access manhole to facilitate maintenance and service without stopping the entire process.

Key words: Biogas applications; Biogas production; digester design; digester operations.

Introduction

A vast number of countries particularly in the developing world are facing an energy crisis(Kabeyi 2022; M. J. B. Kabeyi & O. Olanrewaju 2022). The national energy drivers of all countries globally are energy security, environmental protection, and economic growth (M. Kabeyi & O. Olanrewaju 2022). Additionally, international treaties like Agenda 21, Kyoto Protocol and the Paris agreement of 2015 advocated for a transition to renewable and low carbon sources of energy due to high greenhouse gas emissions associated with fossil fuel and the related climate change caused(Abanades et al., 2021; Sahota et al. 2018). Biogas has significant potential as a renewable energy source for industrial as well as domestic applications and is therefore an efficient solution to the global energy crisis (Achinas et al. 2017; Kumar et al. 2018). The increasing use of fossil fuels and environmental concerns over greenhouse gas emissions and climate change has generated interest in biogas as an alternative renewable energy resource as a substitute(M. Kabeyi & O. Olanrewaju 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022a; Pasternak 2021). Increasing environmental and policy concerns and measures have generated increasing interest in the use of biomass resources as renewable feedstock for electricity generation, fuels production, chemicals processing and hydrogen production. This has been further compounded by depletion of fossil reserves, growing organic waste production and global warming threats which combined have increase interest in anaerobic digestion and biogas fuel resources(Tagne et al. 2021). The main application for biogas is electricity generation, thermal applications like cooking, heating, and lighting, and production of biofuels. Over 7000 MW of electric power is generated from biogas annually(Herz et al. 2017).

Bio-digestion in digesters can be used to address energy, environmental, and health issues among rural communities. Bio-waste i.e. plant waste, animal and human excrement, are placed in the digester to decompose under controlled conditions for optimum production of biogas for use as fuel and to heat homes while the remaining waste can be used as organic for local farms and gardens. Biogas can be used to reduce the amount of plant waste used as fuel thereby

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reducing deforestation and exposer to the toxic smoke and fumes from traditional stoves burning firewood and charcoal. Therefore biogas digesters contribute to environmental sustainability and health improvement of rural communities (Luegenbiehl & Clancy 2017).

Agriculture is the main economic activity for over two thirds of the world population besides supplying food to the entire mankind (Sarkar et al., 2020). Additionally, smallholder agriculture and associated sectors constitute the main economic activities for many developing countries, accounting for about 82% world's population directly or indirectly (Sarkar et al. 2020). Development and adoption of technologies that conserve resources and income in agriculture are the most valuable tools and strategies for sustainability in food and energy production (Kabeyi 2012; Kabeyi 2018; Sarkar et al. 2020).

Biogas, Biomass and Biofuel are all renewable energy sources existing in different phases of the transformation. Biogas can be made from different biomass like poultry droppings, agricultural crops wastes, and cattle manure by controlled anaerobic degradation. Produced biogas can be processed further and concentrated to produce biomethane which can be injected into natural gas pipelines(Farzaneh-Gord et al., 2020). Biogas which is a byproduct of microbial metabolism can be used in its raw form for heat and power generation or can be upgraded to biomethane and for production of value-added chemicals for energy and industrial process application(Pasternak, 2021). The use of biogas can reduce greenhouse gas emissions as it has huge potential for use as a renewable resource(Kabeyi & Olenwaraju, 2020; Kabeyi & Oludolapo, 2020a, 2020b). As an example, 0.29% of total energy consumption in Switzerland for the year 2014 was in the form of biogas and it accounted for close to 8% of the total renewable energy production without accounting for hydropower (Holliger et al., 2017). Biogas can be used to reduce dependence on solid biomass like firewood as a cooking fuel. Biogas has a potential to provide clean cooking fuel for about 200 million people by the year 2040, particularly in Africa and Asia(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & O A Olanrewaju 2022).

Biogas as a fuel has significant benefits as a renewable energy resource while its production process can lead to treatment of feedstock during the digestion, and also produce digestate which is a useful organic fertilizer that can substitute chemical fertilizers in sustainable agriculture (Kabeyi & Oludolapo, 2020b; Lebuhn et al., 2014). The gas has a significant role to play in the global energy transition because of the need to transform the global electricity systems from fossil fuel-based generation to low carbon and renewable energy-based power generation. With huge biomass to biogas conversion potential and many feasible biogases to electricity conversion technologies, biogas will play an extremely important role in the energy transition as a renewable energy fuel resource and feedstock for industrial production of chemical fuels and renewable products (Kabeyi, 2019b; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b; Kabeyi & Oludolapo, 2021a, 2021f; Machado et al., 2021). Microbially-controlled generation of biogas is a significant part of the global carbon cycle where we have a natural anaerobic biodegradation estimated to generate 590–800 million tons of methane into the global atmosphere (Bond & Templeton 2011).

Biogas production provides a way to integrating rural communities and industries to the global energy transition (IEA, 2020). Biogas is methane reach renewable energy resource produced by anaerobic digestion of organic matter under controlled conditions (Arogo et al. 2018; Tanigawa, 2017). Biomass substrate is used for biogas production as long as it contains cellulose, hemicellulose, proteins, fats and carbohydrates that that are indigestible (Das et al., 2020). Biogas has multiple applications in heat and electricity production as well as a raw material for production of several biofuels and can also be used for production of biomethane, carbon dioxide and hydrogen (Energypedia, 2016). The energy content of biogas is a function of methane composition which is influenced by the process and the substrate type used in its production. Biogas may also contain constituents like Sulphur which make it undesirable as a fuel for internal combustion engines and many other industrial chemical and thermal applications. The calorific value of biogas varies with composition and is mainly determined by the proportion of methane. The heating value generally varies from 21-23.5 MJ/m^3.

Humanity initially relied almost entirely on biomass for his energy needs before the 1800s (Moriarty & Honnery, 2019). The industrial revolution led to a transition to fossil fuels dominated energy mix led by coal and later petroleum products like diesel and natural gas. The early 1970s to late 1980s witnessed high increase in oil price which necessitated the search and development of renewable, sustainable, and environmentally friendly sources with biogas being among the top sources of alternative energy (Kabeyi & Oludolapo, 2021c, 2021d; Mary et al., 2007). According to (Chen 2017), there is need to conserve the environment and dispose of wastes to prevent environmental degradation and greenhouse gas emissions. Biogas can be produced by rural communities who are a majority in many developing countries living as peasant farmers, for example in India about 70% of the population live in rural areas (Palit et al. 2013), but the huge energy potential of biogas is currently underutilized globally. In many developing countries, most of the population live in rural areas as smallholder farmers who can adopt biogas technology for most of their energy needs (Kabeyi & Oludolapom 2021e; Kariuki 2009).

Many small holder farmers in developing countries burn biomass as a means of disposal yet it is a potentially source of valuable fertilizers which can substitute expensive chemical fertilizers. For poor smallholder farmers, biogas technology can be used to produce organic fertilizer to supplement expensive chemical fertilizers (Energypedia, 2018). On the design aspect of the study, it is necessary to define the different parameters needed to ensure that rural household can continuously meet their total energy needs through of biogas (Kariuki 2009). Although biogas is mainly used in direct heat application, electricity generation and fertilizer production will help maximize the benefits from investment in a bio-digester with multiple benefits of agriculture, electricity supply for electrical needs of farms and households alongside traditional biogas heating application. With more than 7 types of biogas digester designs currently developed, there is need to give a proper guideline on the best design that would work on a rural household scenario. Silting is a challenge to digester design, operation and management, there is need to control the challenge through design that will limit silting at the bottom of the bio-digester (Kabeyi 2019a; Kariuki 2009). Silting and other operational challenges continue to be a nightmare for smallholder biogas investors. Hence, a serviceable biogas digester design is important to allow for feeding and discharge, repairs or any alteration in the future and maximize the digester effectiveness.

Biodegradable agricultural wastes have a number of environmental impacts that are a concern globally. Livestock waste is estimated as one of the main causes of soil degradation and water resources contamination and is responsible for about 18% of greenhouse gas emissions which include, nitrous oxide which has got about 296 times the Global Warming Potential of carbon dioxide (CO_2), most of which comes from manure. There is therefore urgent need for alternatives to mitigate these environmental effect of agricultural wastes. Agriculture and livestock farming are important economic activities whose sustainability can be enhanced by putting wastes and byproducts environmentally friendly value addition like biogas production (Yanela et al. 2019).

Biogas Production and Use

As concerns grow over unstable price of crude oil products, growing concerns over greenhouse gas emissions and need to transition our fossil fuel based energy system to renewable energy, biogas from biodegradable wastes has emerged as a leading alternative energy resource for the transition(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022b; Kabeyi & Oludolapo 2020c). Before the emergence of fossil fuels as main source of energy, biomass mainly in form of wood, supplied about 90% global energy needs. Biogas has many potential applications as substitute for fossil lime kerosene for cooking, engine fuel substitute for petrol and diesel, wood and Charcoal substitute in coking. The composition of methane in biogas is the main determinant of its combustion efficiency but biogas is combustible generally when methane composition is at least 50%. Biogas can be used in power generation as a biofuel for engine prime movers and feedstock for hydrogen production and direct application in fuel cells (Aralu et al., 2021; M. Kabeyi & O. Olanrewaju 2022; Kabeyi & Olanrewaju 2021b; Kabeyi & Oludolapo, 2020b).

Biogas Production Process

Biogas is generated from different organic matter through anaerobic digestion. Anaerobic digestion is the culmination of different chemical and biological processes that organic matter goes through for biogas production and also waste management(Amigun & Blottnitz, 2007). The process of biogas production constitutes systematic breakdown of large organic polymers by anaerobic action of different microorganisms into smaller molecules (Amigun & Blottnitz, 2007; Amigun et al., 2006). Anaerobic digestion for production of biogas from biomass is a chemical process that involves hydrolysis, acidogenesis, acetogenesis and methanogenesis (Amigun & Blottnitz, 2007; Das et al., 2020).

Biogas is produced by the microbial action in the digestor soon after biomass is prepared and fed into reactor by a gradual fermentation process. Therefore, the process is a result of microbes feeding on the organic matter in form of proteins, carbohydrates and lipids/fats, and whose digestion leads to production of gases mainly in form of methane and carbon dioxide. The stages in biogas production can be classified as pretreatment, hydrolysis, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The process of biogas production starts with feedstock processing or pretreatment before feeding the digester for actual digestion process through anaerobic degradation. Feedstock pretreatment is a necessary procedure to minimize failures, improve generation and quality of digestate among other benefits.

2.1 **Pretreatment Stage**

Pretreatment enhances the substrate degradation and hence the process efficiency. Pretreatment methods can be classified into Chemical, mechanical, thermal and enzymatic processes all meant to speed up decomposition but does not necessarily lead to higher biogas production(Achinas et al., 2017). The pretreatment process generally starts with feedstock cleaning by washing, feedstock maceration, screening and pressing depending on type and status of the feedstock. Impurities like plastic materials are removed, while magnetic traps can be used to remove magnetic impurities, to prevent erosion and damage of moving parts. Pretreatment stage also involves removal of nonmetallic impurities like glass, eggshells, ceramics, bones, and sand which may not be digested as they form solid deposits at the bottom of the digester leading to loss of digestion space(Jain et al., 2019).

Lignocellulose digestion needs the use of enzymes for hydrolyzation. The complex structure of lignocellulosic waste creates an economic and technical limitation for biogas production. Lignocellulose contains cellulose, hemicellulose, and lignin which strengthen linkages between molecules, leading to formation of a compact and strong structure. Biogas generation efficiency of lignocellulose relies on pretreatment performance. Generally, pretreatment fastens reaction and increase the biogas yield and generate a wide range of new substrates for use(Achinas et al., 2017).

2.1.1. Anaerobic digestion process

Hydrolysis

Hydrolysis is a chemical process that involves the breakdown down of water to form OH-anions and H+ cations. Hydrolysis takes place in the existence of existence of an acidic catalyst to break down large biomass polymers in the substrate (Arogo et al., 2018). Biomass has large organic polymers in form of proteins, carbohydrates, and fats, are broken down into simple sugars, fatty acids, and amino acids which are smaller molecules (Amigun & Blottnitz, 2007; Amigun et al., 2006; Arogo et al., 2018). During hydrolysis, fermenting bacteria (FB) like Bactericides, Clostridia, and Bifidobacterial breakdown biopolymers i.e. carbohydrate, proteins, and lipids into sugar, fatty acids and amino acids which are soluble(Kour & et al, 2019). The main products of hydrolysis are acetate and hydrogen which are used in later stages of anaerobic digestions by action of methanogens. Most hydrolysis products are still large molecules that need further break down to create methane through the acidogenesis process (M. J. B. Kabeyi & O. Olanrewaju 2022; Kariuki 2009).

Acidogenesis

This process involves creation of mainly organic acids, alcohols, hydrogen gas, and hydrogen sulfide by the anaerobic action of acidogens (Arogo et al. 2018; Kour & et al. 2019). Hydrolysis products are broken down by acidogenic microorganisms, in an acidic environment created by action of the fermentative bacteria to generate ammonia, carbon dioxide, hydrogen sulfide, carbonic acid, fatty acids with shorter volatility, alcohol, and other trace products based on the substrate composition and products of hydrolysis(Kour & et al. 2019). The products of acidogenesis are still large and therefore are not ideal for methane production. They are therefore subjected to the acetogenesis process (Bond & Michael 2011).

Acetogenesis

Acetogenesis creates acetate, which is from acetic acid (Karlsson et al. 2014). The products of acidogenesis are anaerobically digested to during acidogenesis to produce acetic acid, hydrogen, and carbon dioxide. The digestion by acetogens is done to a point where methanogens can act on products of acetogenesis as well as some products from other processes to generate methane (Bond & Michael 2011).

Methanogenesis

In methanogenesis which is the last stage methane and carbon dioxide are produced because of the action of acetoclastic methanogens (AM) and carbon dioxide (CO_2) reducing methanogens (CM), respectively. The methanogenesis is finished strictly by anaerobic bacteria known as methanogens like Methanosarcina barkeri, Methanosaeta conciliibacteria and Metanonococcus mazei as the final anaerobic digestion which generates methane by methanogens from the final products of acetogenesis as well as other intermediate products from acidogenesis and hydrolysis processes. (Arogo et al., 2018; Karekezi & Kithyoma, 2007; Kour & et al, 2019). The use of carbon dioxide and acetic acid from the first three steps in creating methane in methanogenesis are:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

The main methane creation mechanism in this stage is the path involving acetic acid even though carbon dioxide (CO_2) could be converted into water and methane. Hence through the acetic acid path, CO_2 and methane are created as the main products of anaerobic digestion (Bond & Michael 2011). Therefore Methanogenesis metabolizes gas mixtures (H_2 and CO_2) into biogas with CH4 (60–70%) and CO2 (30–40%) in composition (Sarkar et al., 2020). Figure 1 below shows the three stages in biogas production and related activities and bacteria.

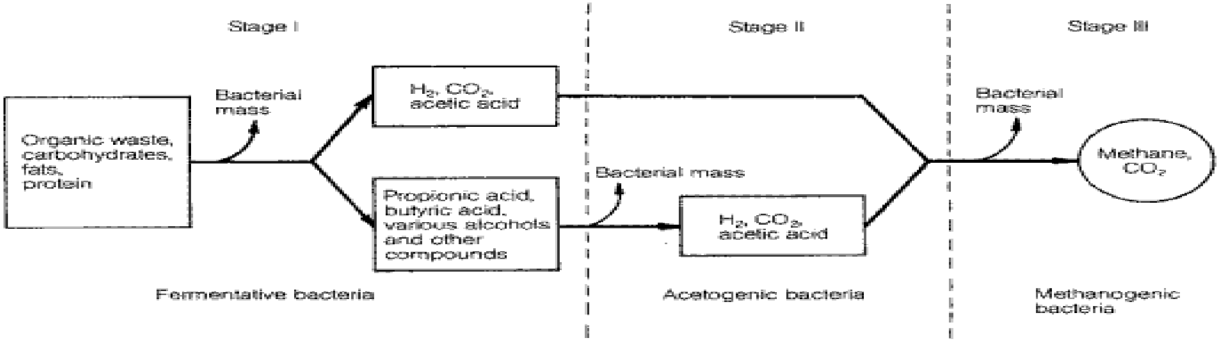

Figure 1. Summary of the biogas formation process (Energypedia 2018)

Figure 1 summarizes the process into three stages with hydrolysis and acidogenesis combined.
From figure 1, it is noted that biogas production is divided into three main stages i.e., stage I which involves the action of fermentative bacteria, stage II which involves action of acetogenic bacteria and stage III which involves action by methanogenic bacteria. Proper management of the three stages ensures optimum production of biogas.

2.5.2. Factors influencing digester's efficiency and performance

i.) Temperature

Application of heat to reactions normally accelerates the process within acceptable limits. This applies to biogas production processes too. The microorganisms in an anaerobic digestion are thermophiles which undergo thermophilic and mesophilic digestion. The thermophiles operate efficiently at temperature range of 45-80°C while mesophilic bacteria work well at temperature range of 25-40°C (Bond & Michael 2011).

ii.) Digester instrumentation

It is important to constantly measure the production level and parameters in any anaerobic digester to identify, biomass quantity, any abnormalities and the well-being of microorganism for efficient and optimum process control and hence output(Karekezi & Kithyoma, 2007). The gasses emitted should indicate how much biomass is not yet broken down and the time to be used. This help in identifying when new biomass should be added and the effectiveness of the digester. In a system where biomass is added a continuously, measuring the gas produced helps in ensuring that the microorganisms are at their peak digestive capability (Bond & Michael 2011). Measuring the gas also indicates any abnormalities in the digester like change in pH and temperature that will affect the gas production.

iii.) PH

The acid forming bacteria work best at a PH of about 5 while the methane forming bacteria flourish at a PH above 6.2 (Arogo et al. 2018). Generally the bio methane process bacterial population flourishes over a pH range of 6.5 to 8.0 with an optimum range of 6.8 to 7.2 (Ghimire & C 2009). Therefore, any deviation from this range makes the digester acidic or basic and hence inhibit methane production. The health of the microorganism is quite crucial in the creation of methane and hence a good environment is required for them to live and prospers. Without the microorganism, the digester will not be able to produce the required gas. Hence this should be measured at all times (Karlsson et al. 2014; Kemausuor et al. 2018).

iv.) Carbon Nitrogen ratio (C/N ratio)

This is the ratio of total carbon and Nitrogen in the substrate. A ratio from 20 to 30 is recommended for anaerobic digestion while very high ration of C/N enhances the growth of methanogens population which results in little or no action on the leftover carbon in the substrate leading to low methane production. A too low C/N ratio leads to high ammonia which then become toxic for methanogenic bacteria and thus low methane production (Karlsson et al. 2014).

Toxicants

Toxicants include antibiotics and other residues which inhibit methanogenesis, hence reducing methane the production and instead increasing the concentration of volatile acids. High nitrogen to carbon ratio is more likely to lead to toxic conditions for the bacteria and so should be avoided (Arogo et al. 2018).

i.) Loading time

Loading rate is the amount of volatile solids fed to the digester per day per unit volume of the digester (Arogo et al., 2018). High loading rates are desirable for higher methane production.

ii.) Red Ox conditions

In the digester, the methanogenic bacteria require redox condition in the range of -300 and -330 mV for optimal performance (Bahaa et al. 2007).

2.2. **Process Energy Requirements**

Biogas production process requires energy input in form of heat to maintain the temperature within range and regular stirring of the substrate manually of by electric motor driven stirrer(Karlsson et al., 2014). Heat energy required can be obtained by recovery and recycling of waste heat in the digester effluent. This can result in a 2–3 °C temperature rise of the slurry at inlet. Thus can lead to energy saving of about 50% total heat requirement in thermophilic digesters(Han et al., 2016; Kabeyi & Oludolapo, 2021b). For large and medium digesters, external heating is more suitable. It is less efficient than internal heating requiring almost two times the rate of internal heating. Typical values are 850–1000 $W/m^2 K^{-1}$ for external heating and 300–400 $W/m^2 K^{-1}$ for internal heating (Han et al., 2016).Biogas production involves control of technical and economic parameters like microorganism species, feedstock pretreatment and biogas purification processes, substrate composition, substrate [properties and optimal reactor conditions. Cost effective production of biogas is dependent on optimization of the combination of these parameters, There is need for further research to improve biogas production and biogas use by use of engineering and biology/biotechnology, and technological innovations (Achinas et al., 2017; Stucki et al., 2011).

3. Design Methodology

Proceudre

The first stage in the digester design is to obtain information concerning where the bio-digester will be located, with emphasis on the physical-geographical and climatic characteristics. The second stage involves collection of data to assist in sizing or determining the capacity and volume required based on demand and availability of feedstock. In the third stage of design a proposed general form of the design is proposed with calculations generated from the information gathered. This is presented in the form of drawings to for easy understanding and analysis of them bio digester. The fourth stage involves design calculations for production of the digester based on demand of gas and feedstock availability to establish optimum design specifications(Yanela et al., 2019).

3.1 Feedstock for digesters

Any biodegradable biomass is potential feedstock for bio digesters in right proportions and conditions of the digester. Biomass refers to organic matter animal or vegetable origin and is considered as the stored energy of living organisms. In the natural cycle, Plants and animals take advantage of biomass in the natural cycle appropriating its power to support their lives. The part of biomass not consumed or used is considered as residual biomass. It is the residual biomass that becomes a very useful resource for production of energy to support life. Animal waste and crop residues as well as natural forests produce biomass which has significant energy potential through direct combustion or through thermal and bio- chemical processes like anaerobic digestion and fermentation for fuel production and power generation(Yanela et al. 2019).

Biomass has two main treatments:
Thermochemical methods which use heat as a source of transforming dry biomass like straw, wood,
Biochemical methods which require presence of microorganisms like bacteria to process or transform biomass to other forms of energy e.g. biogas production in anaerobic digestion or alcohol production by fermentation.

Anaerobic digestion is one of the most important biochemical methods used to treat biomass with high moisture content and lower calorific value under controlled conditions in a bio-digester to produce biogas and digestate waste material (Yanela et al. 2019)

4. Biogas Digesters

4.1. Bio digester designs

There are basically three types of biogas plants globally which have undergone significant modifications to improve them in different aspects and to develop different designs but with the same original idea of the three basic types. (Ghimire & C, 2009). The three basic biogas plants are the floating gas holder biogas plant, the fixed dome biogas plant and the fixed dome with expansion chamber biogas plant.

Floating dome biogas plant
This design is, a digester is built underground using brick masonry and has an inlet and outlet. The top of the digester is covered using a floating steel gas holder that is commonly used in collecting the generated gas (Karekezi & Kithyoma, 2007). Depending on the accumulated gas, the floating steel gasholder moves up and down and commonly guided using a central guide pipe. The floating steel gasholder which is commonly fabricated using mild steel tends to account for more than 40% of the entire plants' cost and makes this design a little bit expensive. Through the floating gasholder, the pressure in the digester is retained at a constant (Ghimire & C, 2009). When gas is generated in the digester, the gasholder rises hence giving a signal that gas should be harvested from the plant and lowers where there is no gas(Kabeyi & Olanrewaju, 2020; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022c). The floating dome biogas plant is shown in figure 2.

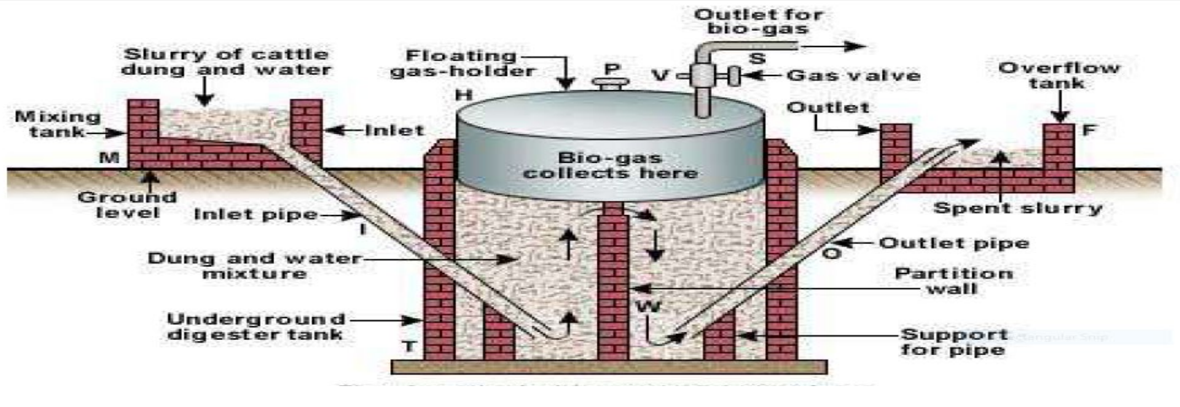

Figure 2. Floating Dome Biogas Plant

From figure 2, the main features of the floating dome digester with the floating gas holder above the digestion space.

Fixed dome biogas plant

In this design, the digester is combined with the gas holder with the upper part of the digester acting as the gas holder. When gas is generated from the slurry, it occupies the top part of the digester and hence the pressure exerted by the gas pushes the slurry in the digester lower as it continues to build up (Karekezi & Kithyoma, 2007). This digester is commonly built below ground level and hence is very suitable for cold regions (Ghimire & C, 2009). Since steel parts are not required in this construction, the construction cost is reduced significantly, and locally available material can be utilized. The fixed dome digester is demonstrated in figure 3.

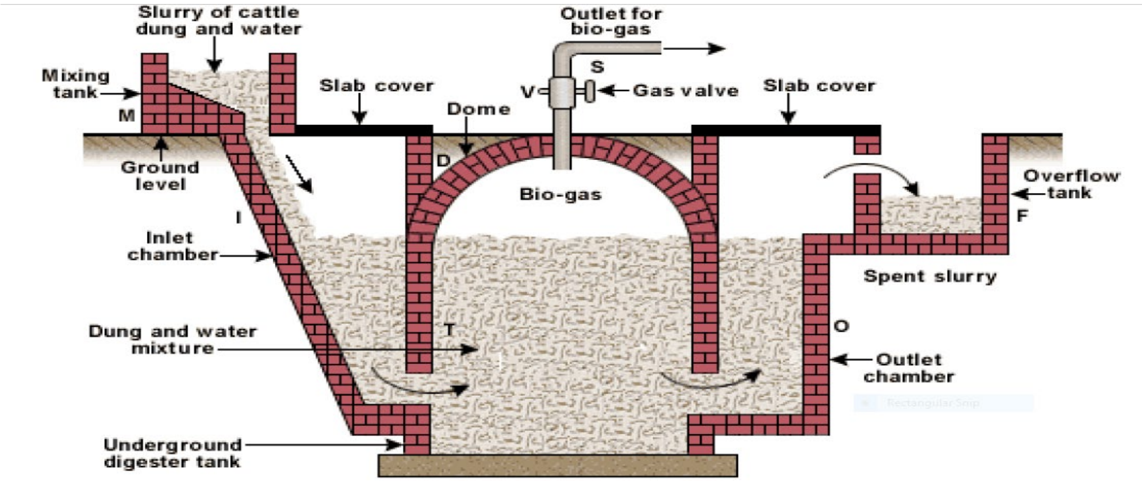

Figure 3. Fixed Dome Biogas Plant

From figure 3, it is observed that the gas produced is held in rigid space above the digestion space. The digester is rigid and lacks flexibility for repairs or service without interrupting operations.

Fixed dome with expansion chamber biogas plant

Just like the fixed dome biogas plant, the digester and gas collector are not separated. However, it has a hemispherical top and a curved bottom which are joined together at their bases, hence no cylindrical part is archived in the middle. The inlet side does not have a displacement space and hence the used slurry is moved to with expansion chamber Biogas Plant. Figure 4 shows a digester with fixed dome and expansion chamber(M. Kabeyi & O. Olanrewaju 2022; Kabeyi & Olanrewaju 2021a).

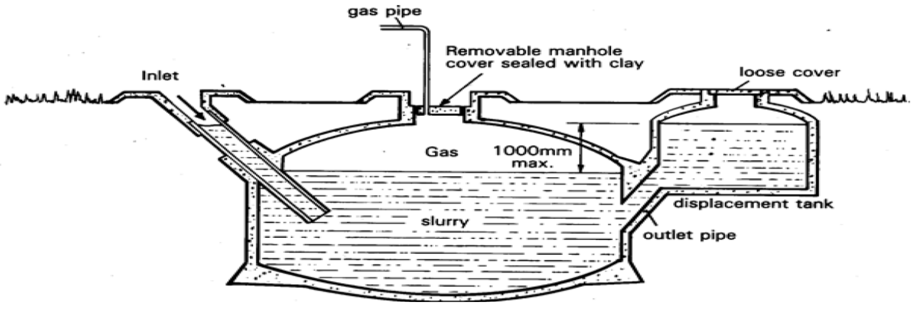

Figure 4. Fixed dome with expansion chamber digester

From figure 4, it is that the fixed dome digester with expansion has a removable manhole cover above the gas space right above the digestion space.

4.2. **Digester Operation and Maintenance Characteristic**

For proper management of biogas production and hence optimum performance, a biogas digester should meet the following requirement;

Mixing capability.

Due to the design nature of the fixed dome design. Once the slurry is poured into the inlet, the slurry is not disturbed until it overflows at the outlet. This has resulted in the unspent slurry and hence losing a lot of methane gas in the process. It also makes it difficult for methane gas to travel from the bottom of the pit towards the gas holder part in the digester in a situation that there is a lot of slurry in the digester. Constant mixing of the slurry in the digester would improve the methane gas production from the digester (Hivos, 2009; IRENA, 2018).

Silting

In most cases, the bottom of the digester we find a very fine and thick silt from the animal dung that builds up with time and reduces the effectiveness, and life span of the fixed dome digester. Removing the silt using the available opening is extremely difficult and reduces the structural integrity of the digester and hence a shorter life span (Hivos, 2009).

Serviceability

The internal structural integrity of the fixed dome design needs to be checked from time to time and ensure for any gas leaks. It is also difficult to retrieve foreign objects it without damaging the digester (Hivos, 2009; Karanja & Kiruiro, 2003). Based on operation and maintenance requirements of the three bio-digester designs most preferable design for a typical rural farm and household would be the fixed dome biogas design. This is due to low maintenance cost and a long life span (Hivos, 2009). The solutions to the issues raised will form the basic design of a better

4.3. **Digester Design Methodology**

The overall objective of the design is to bridge the gap between the different biogas digester designs and develop an optimum design. This was accomplished through accommodations and adjustment on available designs. Different livestock have different biogas potential since their substrates have different physical and chemical characteristics (Energypedia 2016).

4.4. **Design Outline**

The digester volume includes the gas storage volume and the digester chamber. Actual digester volume can be determined by computing the volume of the digester chamber, storage volume and the manhole (Aralu et al. 2021).

4.5. **Digester Installation Guide**

i.) The digester floor should be in compact and stable ground for digester stability
ii.) The recommended cement- and mixing ration is 1:4
iii.) For plastering of the inside digester wall, recommended ration is 1:3
iv.) External mud plastering of the dome should be undertaken after the construction of the dome is completed.
v.) The dome setting should be protected from the sun and given about 6 days for proper curing to take place.

According to (Karanja & Kiruiro, 2003), for a typical a rural farm establishment, operation and maintenance costs can be minimized since main activity is feeding the digester with fresh slurry which typically takes less than 30 minutes and with this, it is possible to incorporate this activity the day to day running of the dairy farm and avoid extra labor.

4.6. **Operation/production**

Bi- digestion involves conversion of biomass through successive oxidation and reductions the most oxidized state i.e. carbon dioxide (CO_2) and its reduced i.e. Methane (CH_4) through the action of microorganism in an oxygen deficient environment(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c). A bio digester is fed with well mixed feedstock with water preferable in the ratio of 1:1. Upon initial loading, biogas may be realized over a period of about 7 days but may vary based on the condition of the biodigester and feedstock. Biogas produced can be collected by opening the valve to the gasbag or other form of gas storage after loading. The gas produced can be monitored for quality and quantity to establish the process performance for improvement if necessary(Aralu et al., 2021; Yanela et al. 2019)

5. Results and Discussion

There are four main stages in biogas production from biomass namely; hydrolysis, acidification, acetogenesis/dehydrogenation and Methanogenesis. The composition of biogas varies but is generally composed of is mainly Methane (50–75%) and CO_2 (30–50%) traces of hydrogen sulfide, nitrogen, hydrogen and carbon monoxide(Aralu et al., 2021; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a; Kabeyi & Oludolapo, 2020a, 2020b). This study has examined various aspects of aspects of the design and operation of biogas digesters with review of a three basic digesters and suggested modifications. The digesters are may be plug flow, floating drum and the fixed dome digesters. Various factors influence anaerobic digestion such as the pH value, feeding material, temperature, pressure, organic loading rate, retention time and the Carbon-to-Nitrogen (C/N) ratio. The design of a bio-digester should consider factors like of the digester shape and construction materials

5.1. Challenges of Biogas Energy Development

Various challenges limit the development of biogas technology adoption particularly for developing countries:

i.) Poor operation and maintenance

There is poor digester operation and maintenance partly due to limited knowledge and partly due lack of interest and commitment. This leads to low biogas production and in some cases total failure of the project

ii.) Lack or Low technological awareness.

Many biogas producers and users are not aware of the working principle of the biogas technology hence limited production and use of biogas resources

iii.) High Installation cost

High volumes of biogas technology installation cannot be undertaken due to lack of capacity in terms of technician and artisans. There also lacks specific Biogas installation materials and adjustments needs to make from what is available in the market.

iv.) Lack or poor post installation support.

Lack of capacity in terms of technicians and artisan with proper biogas technology has resulted in limited post installation support. In situations where a “12-month guarantee period” is given after installation, support tends to seize immediately after the period. The farmers or operators also have little knowledge on the maintaining the systems due to poor technological knowhow.

v.) Limited or lack of Industry Standards

Biogas technology operates freely without any laid-out standards to regulate it. This makes it hard to ensure quality control measures are undertaken.

vi.) Limited awareness and capacity building

There are very few institutions that promote biogas technology in many countries and hence it is not a popular energy source (Bond & Michael 2011; Cucchiell et al., 2017; United Nation Economic and Social Commission for the Asia and the Pacific, 2007).

5.2. Challenges of Digesters and Biogas Productions

Some of the challenges facing digesters are;

i.) Limited mixing capability.

The use of fixed dome leads to unspent slurry and hence lost methane production. Lack of mixing makes it difficult to for methane to move from the bottom of the digester the gas holder of the digester. This problem can be solved by introduction of a mixing devise or system (Harris, 2013; Hivos, 2009).

ii.) Silting

The bottom of the digester is often filled with silt from the feedstock which leads to reduced effectiveness, and life span of the fixed dome digester. Desilting the available opening is extremely difficult and reduces the structural integrity of the digester and hence a shorter life span (Hivos, 2009). The proposed modification is introduction of a service opening at the top if the digester which remains shut at all moments when the digester is in operation The opening is used to remove any silt at the bottom of the digester during maintenance.

iii.) Serviceability

The internal structural integrity of the fixed dome design needs to be checked from time to time and ensure no leakages from the body. The digester is often damaged while removing undesirable foreign objects which may interfere with digester operations (Harris, 2013; Hivos, 2009). Introduction of a service manhole will facilitate limited interference to remove undesirable material without stopping to remove everything which adversely affects digestion.

5.3. Types of Digesters

There are three basic biogas digester designs with distinctive design and operational features. The features and differences are summarized in table 1 below.

Table 1. Comparison of the Three Basic Digester Designs

	Properties/ Designs	Floating Gas Holder Design	Fixed Dome Design	Fixed Dome with Expansion Chamber Design
1	General Setup	Deep well shaped digester with masonry structure. There is a partition in the middle of the digester.	Shallow well shaped digester with masonry structure. No partitioning of the digester.	Two sphere segments placed on top of each other makes the digester.
2	Biogas Holder	Gas holder is fabricated using mild steel and inverted on the digester. It rises and down with the generation and utilization of gas.	Gas holder is part of the digester's masonry structure. Slurry is displaced downwards with gas formation and comes up when gas is used.	Gas holder is part of the digester structure and gas is stored in the same way as the fixed dome design.
3	Gas Pressure	Constant gas pressure. About 10cm of water.	Varies from 0 to 90 cm of water.	Varies from 0 to75cm of water.
4	Maintenance	High cost of maintenance due to corrosion on the gas holder.	Low maintenance cost. No steel is used.	Low maintenance cost. No steel is used.
5	Life span	Short life span	Long Life span	Average life span
6	Extra Features	Easy to know how much gas is produced.	No recurring expenditure as there are no moving part.	No recurring expenditure as there are no moving part.
7	Required construction	Less excavation is required	More excavation is required.	High excavation is required
8	Construction	Gas holder fabrication should be done by an expert. The digester can be built by trained mason.	Locally available material can be utilized by a trained mason.	Locally available material can be utilized by a trained mason.
9	Installation cost	Higher installation cost.	Average Installation cost.	Low installation cost.

From table 1, it is demonstrated that the three basic designs of bio-digesters have distinctive features which make them unique to one another. Design and operational requirements which are different include gas pressure, estimated lifespan, construction of the gas holder, installation cost and general setup.

5.4. Recommended Improvements

Various weaknesses are identified for existing digesters that can be addressed by modifying existing digester designs. The identified features for an improved digester are;

i.) **The** mixing challenge can be solved by introducing a mixing component inside the digester to ensure that constant mixing is archived and increase the productivity of the digester. For designs targeting the rural farm and household setup, we will introduce a mechanical setup for mixing which can be done using hands as opposed to motorized or electrical mixers due to high-cost installation.

ii.) The problem of silting can be improved introducing a service opening at the top if the digester when fixed dome is used. This opening will remain shut at all moments when the digester is in operation and will not allow gas to escape.

iii.) The challenge of digester serviceability is addressed introducing an opening in the digester for service and maintenance access when required to minimize process interruptions.

Conclusion

It will take roughly one weak for a bio-digester to start producing flammable biogas from the scratch during which the digester conditions are expected to stabilize. The easiest practical indicator of good quality biogas production is a steady blue flame-from burning biogas produced. A biogas stove can be incorporated in a basic biogas system for cooking purposes while gas produced is compressed into cylinder from the gasbag for storage and future use. Gas flaring is used to prevent methane gas from being released to the atmosphere, and to protect the dome from excessive gas pressure. An agitator and manhole can be installed away from the dome to ensure the integrity of the dome. Feedstock should be mixed in an appropriate C/N ration with the right amount of water for optimum biogas production.

This study demonstrated the important role of digester design, operation and maintenance as a very important aspect of biogas production. There are three basic digester designs i.e. fixed dome, floating dome and fixed dome with expansion chamber with the main challenges facing digesters being silting, poor serviceability and limited mixing ability. Design improvements suggested are manual and motorised mixing and provision of access manhole to facilitate maintenance and service without stopping the entire process.

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