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Review Paper

Challenges and Solutions in Biogas Technology Adoption in Ethiopia: A Review

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Abstract

Biogas is a gas that is produced when organic matter decomposes. Biogas produced by anaerobic digestion may be a viable energy source for rural Ethiopia. It is suitable for cooking as well as generating electricity. There are over 18,000 biogas digesters dispersed throughout Ethiopia, and despite the benefits of addressing energy-related issues like environmental and energy scarcity, the country's use of biogas is not rising dramatically. This article provides an overview of biogas technology in Ethiopia and discusses the obstacles and opportunities associated with its expansion. High initial investment costs for digesters, a lack of biogas substrates, a lack of biogas research, a failure of the biogas pilot phase, a lack of public awareness campaigns, insufficient construction and maintenance expertise, low biogas technology efficiency, minimal biogas application, and a lack of appropriate bio-slurry management were identified as barriers to biogas technology expansion in the country. It was stressed that biogas plants installed throughout the country, particularly in rural areas, should be sized appropriately for the substrate available. Furthermore, the calorific value of biogas should be increased in order for it to be used to power generator sets and internal combustion engines.

1. Introduction

Agriculture, industries, and service sectors all rely on energy to drive economic development. In the current global energy system, fossil fuels in the form of coal, oil, and natural gas are the primary sources of energy; approximately 80% of global energy still comes from fossil-fuel-based systems. Some of the problems associated with these energy systems are (i) they cannot replenish themselves as quickly as they are exhausted, (ii) they are limited, and (iii) having an adverse effect on the environment. Global energy consumption is increasing at a rate of 2.3% per year. The consumption of fossil fuels (coal, oil, and natural gas) has largely met the increased demand (Figure 1) (Ipcc 2014; Mekonnen 2015; Christensen et al., 2017). Renewable energy's contribution to global energy production is steadily increasing. In 2017, it accounted for 18.1% of global energy production, with modern renewables accounting for 10.6% and traditional biomass accounting for the rest (Figure 1) (IRENA, 2012; REN21, 2019).

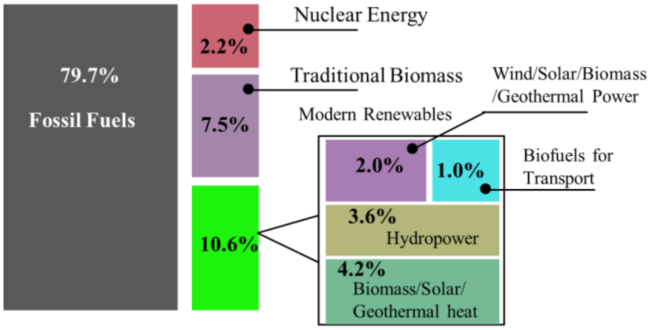

Figure 1: The share of renewable energy in globe final energy consumption (2017) (REN21, 2019).

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Climate change, on the other hand, is among the most serious problems the world faces today (Prasad et al., 2019). Part of the problem stems from the widespread usage of fossil fuels in various sectors. Fossil fuels were first used at the beginning of industrialization and are now responsible for the amplified atmospheric concentration of heat-trapping greenhouse gases (GHGs) (Prasad et al., 2019). According to the IPCC 5th Assessment Report (Ipcc, 2014), non-renewable energy sources emitted 47% of the 10 $GtCO_2eq$ increase in annual anthropogenic GHG emission that occurred in the last decade (2001–2010), followed by industry, transportation, and building sectors with 30%, 11%, and 3%, respectively.

Methane (CH_4), nitrous oxide (N_2O), and fluorinated gases are all significant GHGs in addition to carbon dioxide (CO_2). As a GHG, methane is roughly 25 times more potent than CO_2 (Paolini et al., 2018; Nevzorova and Kutcherov, 2019; Hasan et al., 2020). Methane is produced in nature as a decomposition of plant and animal matter, but there are also natural sinks that remove excess methane (Nevzorova and Kutcherov, 2019; Yasmin and Grundmann, 2019; Hasan et al., 2020). Extra methane, on the other hand, is emitted as a result of human activity. Human activities are thought to have already contributed to roughly 1°C of global warming over pre-industrial levels (Ipcc, 2014). Furthermore, high amounts of methane deplete ozone, reducing the Earth's protection against UV rays from the Sun. Anthropogenic methane is produced through waste (for example, landfill gas, municipal wastewater, and solid waste), agriculture (e.g. livestock), and industry (e.g. fossil fuel production). The methane produced by these sources may be utilized to make biogas, lowering GHG emissions while conserving energy and material resources. Biogas has a high calorific value and may be used to substitute coal, oil, and natural gas, which can assist to reduce GHG emissions.

Biogas energy generation has the potential to turn a "costly problem" into a "profitable solution" (Nevzorova and Kutcherov, 2019; Yasmin and Grundmann, 2019; Hasan et al., 2020). Biogas can be utilized efficiently in simple gas stoves for cooking as well as lamps for lighting. Furthermore, because of its high phosphorus content, biogas sludge may be used to produce biofertiliser for farms, which is predicted to minimize the need of chemical fertilizers and pesticides (Luostarinen et al., 2009). Some of the biogas producing materials (substrates) range from animal dung to household, agricultural and industrial wastes (Akinbami et al., 2001). The agriculture sector has the most underutilized resources for biogas generation (Nevzorova and Kutcherov, 2019). Animal husbandry is the primary cause of pollution in rural regions. Unorganized emissions from collecting ponds and manure storage facilities, which emit hazardous chemicals, are the primary causes of pollution in this sector (Hasan et al., 2020). The anaerobic treatment of animal waste in biogas plants offers numerous advantages, including a significant decrease in environmental pollution and pathogens, the removal of odors associated with livestock production, and a reduction in hazardous emissions into the atmosphere.

Biogas is produced during the anaerobic fermentation process, which also disinfects the waste. Anaerobic fermentation of animal wastes might fulfill the energy demands of the husbandry sectors entirely or substantially, while also creating important organic fertilizers that can greatly lower the operational costs of biogas facilities. Biogas, unlike biodiesel and bioethanol, is mostly created from organic waste and does not contribute to issues such as food scarcity or biodiversity loss. As a result, biogas is a more ethical alternative for energy generation (Rittmann, 2008; Manon and Bermúdez, 2016; Chala et al., 2018; Faisal et al., 2018). Rising greenhouse gas emissions, increasing consumption, water pollution, diminishing soil fertility, poor waste management, and deforestation are all consequences of inefficient use of natural resources across the world. Biogas as an energy source is an essential component in the chain of actions to address these issues. However, realizing the full potential of biogas is taking time, and adoption varies depending on the available sources. As a result, biogas energy supply is typically relatively low when compared to other bioenergy sources (Figure 2).

Ethiopia's economy is one of the fastest growing in Africa, but it has one of the world's poorest access to modern energy supplies. The majority of Ethiopia's population lives in rural areas and is heavily reliant on agriculture; biomass (biomass of wood, solid, and agricultural wastes) is the primary source of energy for this rural population, accounting for approximately 87% of total energy supply (Berhanu et al., 2017). Nonetheless, the current energy systems in rural and urban areas differ significantly. Almost all rural households use traditional biomass for cooking and baking, whereas nearly 90% of urban residents use electricity for lighting. Ethiopia has enormous biomass energy potential, such as biogas, but it is being underutilized.

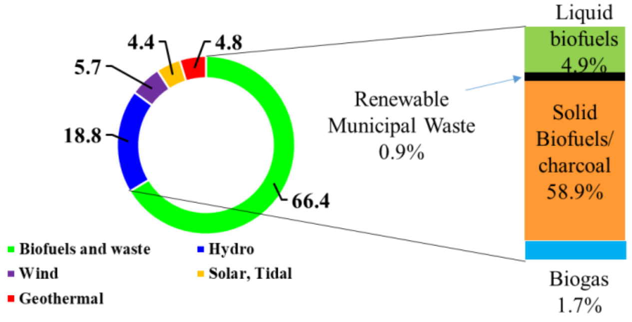

Figure 2: 2018 product shares in world renewable energy supply.

Despite its reliance on traditional energy sources, the country is gradually shifting away from nonrenewable energy sources and toward a clean, renewable energy supply. Energy demand is currently increasing at an alarming rate due to the fast-growing economy and flourishing infrastructures (Berhanu et al., 2017). As a result, at its best, finding an alternative energy source to overcome the issues associated with traditional biomass energy sources could be advocated.

Therefore, it is critical to understand the major problems that are presently impeding the widespread adoption of biogas as a source of energy, as well as potential solutions. While there have been some studies focused on the challenges and prospects of renewable energy in general (Toklu, 2017; Tiruye et al., 2021), and on biogas in specific locations (Etsay et al., 2017; Nevzorova and Kutcherov, 2019; Yasmin and Grundmann, 2019; Hasan et al., 2020; Shallo et al., 2020). There has been no current, comprehensive review of the challenges and possible solutions to the increased use of biogas in Ethiopia. To remedy this gap, the purpose of this article is to give a comprehensive and in-depth assessment of the challenges and solutions in biogas technology adoption in Ethiopia.

2. Biogas: composition, production and applications

2.1.Biogas sources and composition

Biogas is a fuel that is generated when microorganisms degrade organic matter anaerobically (Surendra et al., 2014). Similarly, Ehiri et al., (2014) described biogas as a fuel that is produced when microbes digest organic matter in the absence of oxygen(Ehiri et al., 2014). Organic matter is referred to as substrate and must be biodegradable, for example, domestic waste, primarily kitchen and sewage waste (municipal waste), crop residues and food processing byproducts, and animal dung, such as cow dung, poultry droppings, and pig dungs, among others (Figure 3). However, the definition of biogas makes it abundantly clear that the primary source of biogas is organic matter.

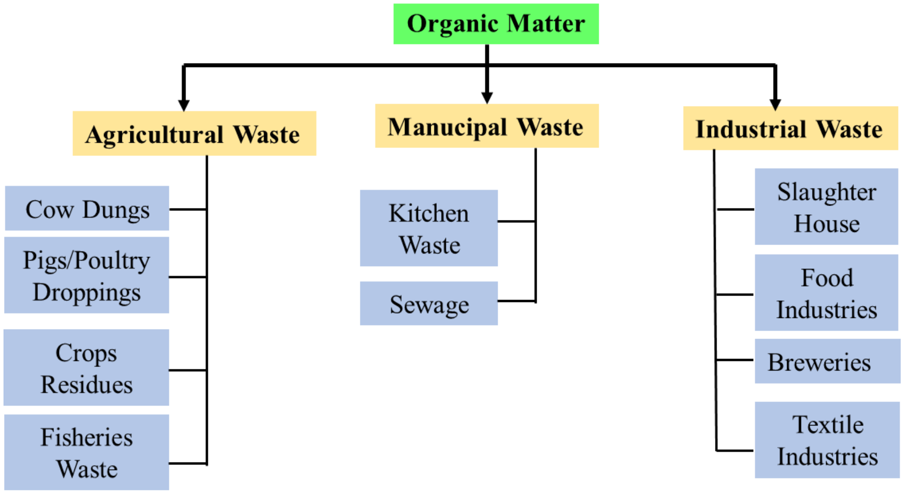

Figure 3: Classification of biogas sources.

Table 1: Chemical composition of biogas and properties of components (Surendra et al., 2014).

Components	Concentration	Properties
CH_4	50–75% (v/v)	Energy carrier
CO_2	25–50% (v/v)	Decrease heating value Corrosive, especially in presence of moisture
H_2S	0–5000 ppm(v/v)	Corrosive Sulfur dioxide emission during combustion
NH_3	0–500 ppm(v/v)	NO_x – Emissions during combustion
N_2	0–5% (v/v)	Decreases heating value
Water vapor	1–5% (v/v)	Facilitate corrosion in presence of CO_2 and sulfur dioxide (SO_2)

Biogas composition varies according to the type of feedstock used and the operating conditions of the digester. In general, biogas contains between 50% and 75% CH_4 and 25%–50% CO_2, as well as trace amounts of water vapour (H_2O), hydrogen sulphide (H_2S), and ammonia (NH_3). Table 1 summarises the typical compositions of raw biogas and the properties of its constituents. Only CH_4 contributes to the heating value of biogas. For instance, 1 m^3 of raw biogas containing 60% CH_4 has a heating value of 21.5 MJ (5.97 kWh of electricity equivalent) per m^3, compared to 35.8 MJ (9.94 kWh electricity equivalent) per m^3 of pure CH_4 at standard temperature and pressure (Surendra et al., 2014).

2.2.Biogas production

The formation of biogas is the result of a series of linked process steps in which the initial substance is repeatedly broken down into smaller units. Each individual step involves a different group of microorganisms. These organisms decompose the byproducts of previous steps in a sequential manner. Figure 4 depicts a simplified diagram of the anaerobic digester (AD) process, highlighting the four main process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

In the digester tank, the process steps depicted in Figure 4 run in parallel in both time and space. The slowest reaction in the chain determines the speed of the total decomposition process. Hydrolysis is the determining process in the case of biogas plants processing vegetable substrates containing cellulose, hemicellulose, and lignin. Biogas is produced in small amounts during hydrolysis. Biogas production peaks during methanogenesis (Seadi et al., 2008).

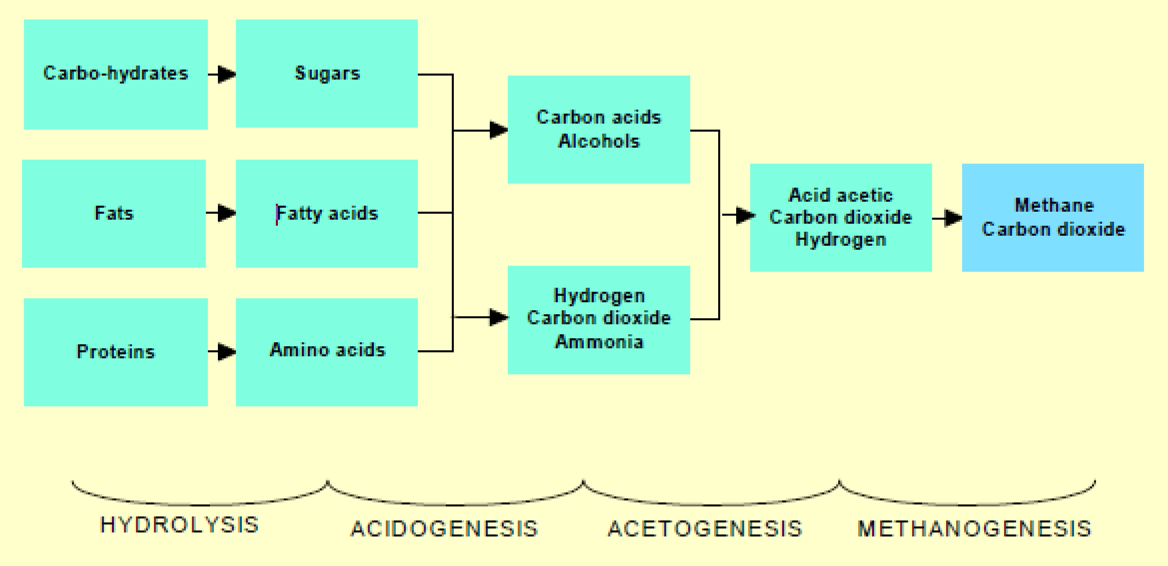

Figure 4: Major stages of biomethanation process (Surendra et al. 2014).

2.2.1. Hydrolysis

Theoretically, hydrolysis is the first step in AD, during which complex organic matter (polymers) is decomposed into smaller units (mono- and oligomers). Polymers such as carbohydrates, lipids, nucleic acids, and proteins are hydrolyzed and converted into glucose, glycerol, purines, and pyridines. Hydrolytic microorganisms produce hydrolytic enzymes, which degrade biopolymers into simpler and more soluble compounds, as shown below (Seadi et al., 2008):

$$\text{Lipids} \xrightarrow{\text{lipase}} \text{fatty acids, glycerol}$$

$$\text{Polysaccharide} \xrightarrow{\text{cellulase, cellobiase, xylanase, amylase}} \text{monosaccharide}$$

$$\text{Proteins} \xrightarrow{\text{protease}} \text{amino acids}$$

Hydrolysis is carried out by exoenzymes produced by the microorganisms that decompose the undissolved particulate material, which involves a wide range of microorganisms. The hydrolysis products are further decomposed and used for metabolic processes by the microorganisms involved.

2.2.2. Acidogenesis

Acidogenic (fermentative) bacteria convert hydrolysis products into methanogenic substrates during acidogenesis. Simple sugars, amino acids, and fatty acids are degraded into acetate, carbon dioxide, and hydrogen (70%), as well as volatile fatty acids (VFA) and alcohols (30%).

2.2.3. Acetogenesis

During acetogenesis, acidogenesis products that cannot be directly converted to methane by methanogenic bacteria are converted into methanogenic substrates. VFA and alcohols are oxidized to produce methanogenic substrates such as acetate, hydrogen, and carbon dioxide. VFAs and alcohols with carbon chains longer than two units are oxidized to form acetate and hydrogen. The partial pressure of hydrogen rises as it is produced. This is a "waste product" of acetogenesis that inhibits the metabolism of acetogenic bacteria. Hydrogen is converted into methane during methanogenesis. Acetogenesis and methanogenesis typically occur in tandem as a symbiotic relationship between two groups of organisms.

2.2.4. Methanogenesis

Methanogenic bacteria are responsible for the production of methane and carbon dioxide from intermediate products. According to the following equations, 70% of the formed methane comes from acetate, while the remaining 30% comes from the conversion of hydrogen (H) and carbon dioxide (CO_2) (Seadi et al. 2008).

$$Acetic\ acid \xrightarrow{\text{methanogenic bacteria}} methane + carbon\ dioxide$$

$$Hydrogen + carbon\ dioxide \xrightarrow{\text{methanogenic bacteria}} methane + water$$

Methanogenesis is a critical step in the anaerobic digestion process since it is the slowest biochemical reaction. The operation conditions have a significant impact on methanogenesis. Factors influencing the methanogenesis process include feedstock composition, feeding rate, temperature, and pH. Overloading the digester, temperature changes, or a large entry of oxygen can all result in the cessation of methane production.

2.3. Anaerobic digester parameters

Some critical parameters influence the efficiency of AD, so it is critical that appropriate conditions for anaerobic microorganisms are supplied. Conditions such as oxygen starvation, constant temperature, pH-value, nutrient supply, stirring intensity, and the presence and amount of inhibitors (e.g. ammonia) all have a significant impact on the growth and activity of anaerobic microorganisms. Because methane bacteria are anaerobes, the presence of oxygen in the digestion process must be strictly avoided (Seadi et al., 2008; Bhajani, 2018; Panigrahi and Dubey, 2019; Sathish et al., 2019).

2.3.1. Temperature

The AD process can occur at three different temperatures, which are classified as psychrophilic (below 25^{o}C), mesophilic (25^{o}C - 45^{o}C), and thermophilic (45^{o}C - 70^{o}C). The process temperature and the HRT have a direct relationship (Table 2) (Seadi et al., 2008; Bhajani, 2018; Panigrahi and Dubey, 2019; Sathish et al., 2019).

Temperature stability is critical for AD. In practice, the operation temperature is chosen with the feedstock in mind, and the required process temperature is usually given by floor or wall heating systems inside the digester. Many modern biogas plants operate at thermophilic process temperatures because the thermophilic process offers numerous advantages over mesophilic and psychrophilic processes (Table 3) (Seadi et al., 2008; Bhajani, 2018; Panigrahi and Dubey, 2019; Sathish et al., 2019).

Table 1: Temperature range and typical retention times

Thermal stage	Process temperatures	Minimum retention time
psychrophilic	< 20 °C	70 to 80 days
mesophilic	30 to 42 °C	30 to 40 days
thermophilic	43 to 55 °C	15 to 20 days

Table 2: Advantages and disadvantages of the thermophilic process

Advantages	Disadvantages
• Effective destruction of pathogens • Higher growth rate of methanogenic bacteria at a higher temperature • Reduced retention time, making the process faster and more efficient • Improved digestibility and availability of substrates • Better degradation of solid substrates and better substrate utilization • Better possibility for separating liquid and solid fractions	• Larger degree of imbalance • Larger energy demand due to high temperature • Higher risk of ammonia inhibition

The toxicity of ammonia is affected by the operating temperature. Ammonia toxicity increases with temperature and can be alleviated by lowering the process temperature. When the temperature is reduced to 50°C or lower, the growth rate of thermophilic microorganisms drops dramatically, and there is a risk of microbial population washout due to a growth rate lower than the actual HRT. Because of the growth rates of thermophilic organisms, a well-functioning digester can be loaded to a greater extent or operated at a lower HRT than a mesophilic one (Seadi et al. 2008; Bhajani 2018; Panigrahi and Dubey 2019; Sathish et al. 2019).

2.3.2. pH-values and optimum intervals

The pH-value is a measure of the acidity/alkalinity of a solution (or, in the case of AD, a substrate mixture). The pH of the AD substrate affects the growth of methanogenic microorganisms as well as the dissociation of some important compounds for the AD process (ammonia, sulphide, organic acids). Experience has shown that methane formation occurs within a relatively narrow pH interval, ranging from about 5.5 to 8.5, with most methanogens preferring a pH range of 7.0-8.0. Acidogenic microorganisms typically have a lower optimum pH value. The ideal pH range for mesophilic digestion is between 6.5 and 8.0, and the process is severely hampered if the pH falls below 6.0 or rises above 8.3 (Seadi et al., 2008). The solubility of carbon dioxide in water decreases as temperature rises. As dissolved carbon dioxide reacts with water to form carbonic acid, the pH of thermophilic digesters is higher than that of mesophilic ones. Ammonia produced during protein degradation or the presence of ammonia in the feed stream can raise the pH value, whereas VFA accumulation lowers the pH value (Seadi et al., 2008; Bhajani, 2018; Panigrahi and Dubey, 2019; Sathish et al., 2019).

The bicarbonate buffer system primarily controls the pH value in anaerobic reactors. As a result, the pH value inside digesters is affected by CO_2 partial pressure as well as the concentration of alkaline and acid components in the liquid phase. If base or acid accumulates, the buffer capacity counteracts these pH changes to a certain extent. When the system's buffer capacity is exceeded, drastic changes in pH occur, completely inhibiting the AD process. As a result, the pH-value should not be used as a stand-alone process monitoring parameter (Seadi et al., 2008).

2.3.3. Volatile fatty acids (VFA)

The concentration of intermediate products such as VFA reflects the stability of the AD process. The VFA are acidogenesis intermediate compounds (acetate, propionate, butyrate, lactate) with a carbon chain of up to six atoms. In most cases, AD process instability results in VFA accumulation inside the digester, which can cause a pH drop. However, due to the buffer capacity of the digester and the biomass types contained in it, the accumulation of VFA will not always be expressed by a drop in pH value. Animal manure, for example, has an excess of alkalinity, which means that VFA accumulation must exceed a certain threshold before it can be detected by a significant decrease in pH value. The VFA concentration in the digester would be so high at this point that the AD process would be severely inhibited. As a result, as with pH, VFA concentration cannot be recommended as a stand-alone process monitoring parameter (Seadi et al., 2008; Bhajani, 2018; Panigrahi and Dubey, 2019; Sathish et al., 2019).

2.3.4. Ammonia

Ammonia (NH_3) is an important compound that plays an important role in the AD process. NH_3 is an important nutrient that serves as a precursor to foods and fertilizers. It is typically encountered as a gas with a pungent odor. Proteins are the primary ammonia source for the AD process. Process inhibition is thought to be caused by excessive ammonia concentrations inside the digester, particularly free ammonia (the unionized form of ammonia). Because of the high ammonia concentration originating from urine, this is a common AD of animal slurries. Ammonia concentrations should be kept below 80 mg/l to have an inhibitory effect (Seadi et al. 2008). Ammonia inhibition is especially sensitive to methanogenic bacteria. Because the concentration of free ammonia is directly proportional to temperature, there is a greater risk of ammonia inhibition in thermophilic AD processes compared to mesophilic ones (Seadi et al. 2008; Bhajani 2018; Panigrahi and Dubey 2019; Sathish et al. 2019).

2.3.5. Macro- and micronutrients (trace elements) and toxic compounds

Microelements (trace elements) such as iron, nickel, cobalt, selenium, molybdenum, or tungsten are as important for the growth and survival of AD microorganisms as macronutrients such as carbon, nitrogen, phosphorus, and sulfur. Inadequate nutrient and trace element provision, as well as excessive substrate digestibility, can cause inhibition and disturbances in the AD process. The presence of toxic compounds is another factor influencing the activity of anaerobic microorganisms. They can be introduced into the AD system alongside the feedstock or generated during the process. The application of threshold values for toxic compounds is difficult, on the one hand because these materials are frequently bound by chemical processes, and on the other hand because anaerobic microorganisms can adapt to environmental conditions, including the presence of toxic compounds, within certain limits (Seadi et al., 2008).

2.3.6. Organic load

A biogas plant's design and operation are influenced by both economic and technical factors. To achieve the highest biogas yield through complete substrate digestion, a long retention time of the substrate inside the digester and a correspondingly large digester size would be required. In practice, the choice of system design (digester size and type) or applicable retention time is always based on a trade-off between maximizing biogas yield and maintaining a justifiable plant economy. The organic load is an important operational parameter in this regard, as it indicates how much organic dry matter can be fed into the digester per volume and time unit (Seadi et al., 2008).

2.3.7. Hydraulic retention time (HRT)

The hydraulic retention time is an important parameter to consider when designing a biogas digester (HRT). The HRT is the average time interval during which the substrate remains in the digester tank. HRT is proportional to digester volume and substrate fed per time unit. The retention time must be long enough to ensure that the amount of microorganisms removed with the effluent (digestate) is not greater than the amount of microorganisms reproduced. Anaerobic bacteria typically duplicate every 10 days or more. A short HRT allows for a higher substrate flow rate but a lower gas yield. As a result, it is critical to tailor the HRT to the specific decomposition rate of the substrates used. The required digester volume can be calculated using the targeted HRT, the daily feedstock input, and the substrate decomposition rate (Seadi et al., 2008).

2.4. Biogas applications

Biogas is a renewable energy carrier that has the potential to be used for a variety of end uses, including heating, combined heat and power (CHP) generation, transportation fuel (after being upgraded to biomethane), and natural gas quality for a variety of end uses (Figure 5). However, in developing nations, biogas is largely used for cooking and lighting through household-scale digesters. This is because the most common digester in poor nations is between 2 and 10 m^3, and the volume of biogas produced by such a digester is insufficient to support CHP or purification into biomethane for other end uses. It should be emphasised, however, that biogas generated by large-scale institutional facilities is being used to generate energy in some developing nations via fuel cells or combined heat and power (CHP) engines, similar to methods used in affluent countries. After cooking, lighting is the second most prevalent application of biogas, particularly in areas without access to the electrical grid. Biogas is used to power lights using customised gas mantle lamps that burn approximately 0.07–0.14 m^3 of biogas per hour and operate satisfactorily at gas pressures ranging from 70–84 mm of water. Figure 5 illustrates the flow of feedstocks through the AD system to produce biogas and digestate.

Biogas recovery and utilization from AD systems often creates significant value in new economic, energy, environmental benefits by managing and converting organic waste into energy and beneficial uses of digestate. Unlike traditional organic waste disposal and manure storage systems, modern AD/biogas systems can be designed to increase and optimize the production of biogas and energy generation, among many other benefits. Benefits of AD/biogas systems include, but are not limited to, generation of various types of energy, including baseload renewable energy generation; odor minimization; generation of nutrient rich digestate; improving the environment by minimizing waste; among many others. The potential and problems associated with the use of biogas technologies are summarized in Table 4.

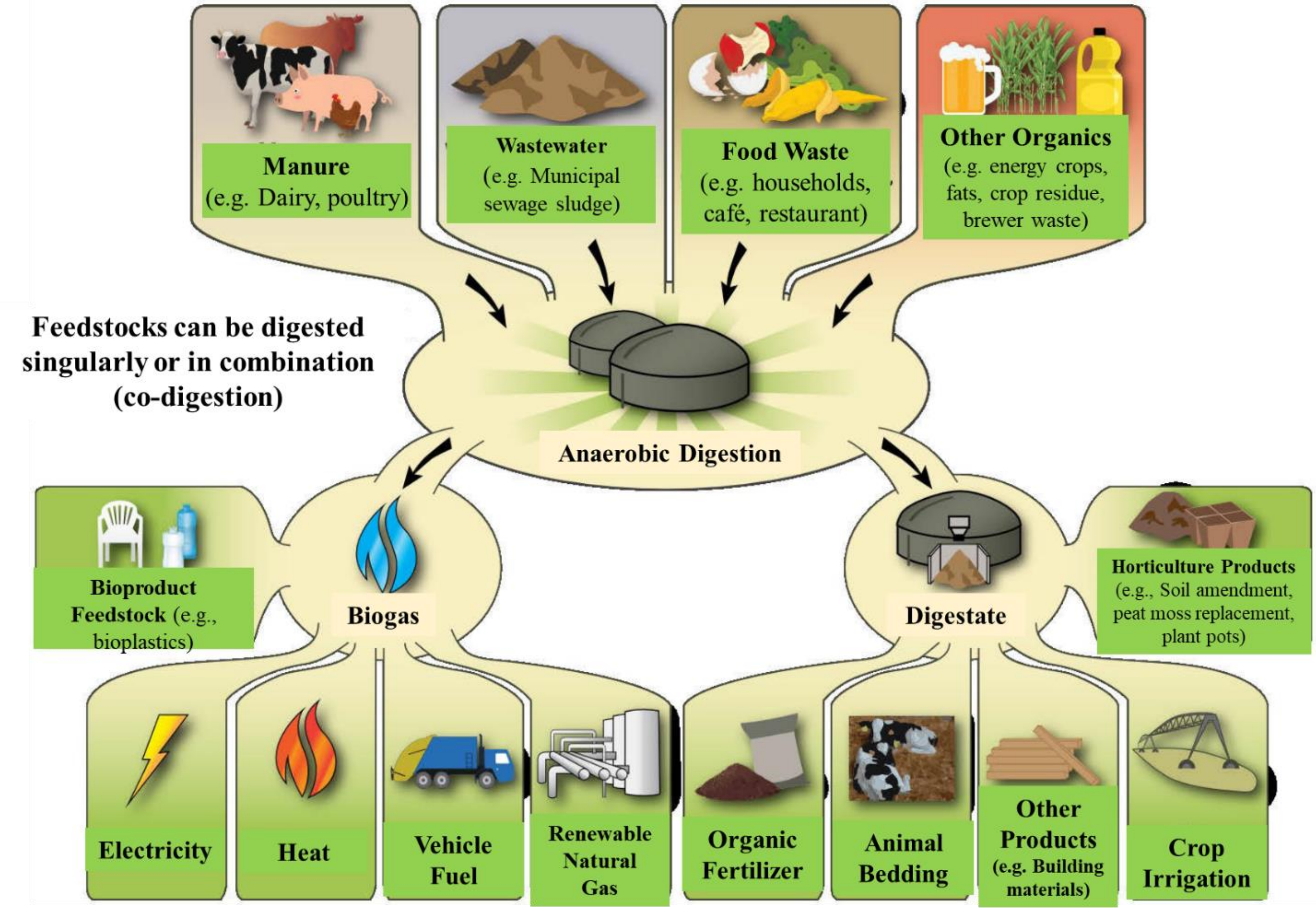

Figure 1: Basic Anaerobic Digestion (AD)/Biogas System Flow Diagram (EPA, 2008).

Table 3: Advantages and disadvantages of biogas (Bhardwaj and Das, 2017)

Advantages of biogas	Disadvantages of biogas
It is a renewable source of energy: The only time when biogas will be depleted is when the production of any kind of waste is stopped. Also, it is a free source of energy.	Little Technology Advancements: Very few technological advancements have been made or introduced for streamlining and making the process cost-effective and hence the systems that are currently used are not efficient enough.
Non-polluting: Biogas is considered to being nonpolluting. The resources are conserved by not consuming any further fuel since the production of biogas does not require any oxygen. It also reduces deforestation and any sort of indoor air pollution.	It consists of impurities: Biogas goes through many refining processes and yet contains several impurities. The metals in an engine can start corroding if this biogas full of impurities is used as a fuel after compressing the biogas.
It reduces landfills: There is a decrease in soil and water pollution since it uses up the waste in landfills and in dumps as well.	Biogas is not attractive on large scale: Large scale usage of biogas is not economically viable. Enhancing the efficiency of biogas systems is very difficult as well.
A large number of jobs are obtained: Due to the biogas plant setups, a major number of work opportunities get created for thousands of people.	Biogas is unstable: When methane comes in contact with oxygen, biogas tends to become flammable. This happens because biogas is unstable and hence it is vulnerable to explosions
The setup of a biogas plant requires little capital investment and is also easy when set up in a small scale.	
Production of biogas takes place by utilizing the gases which are produced by the landfills and hence the greenhouse effect is reduced.	
Biogas slurry can used as organic fertilizer: In contrast to composting and direct burning, biogas digester provides both fuel and fertilizer, rather than simply one or the other.	

3. Methodology

The data was gathered from journals, site visits to biogas digesters, and questionnaires distributed to biogas installers. Site visits for biogas digesters resulted in the recording of observations. The data on issues and challenges with biogas technology was gathered by the authors and from various stakeholders during the installation of some biogas digesters through questionnaires, a literature review, and site visits.

4. Biogas technology dissemination and current status in Ethiopia

4.1. Biogas dissemination

4.1.1. Before 1980

Biogas was first introduced in Ethiopia by Ambo Agricultural College around 1957 to supply the energy for welding agricultural tools (Abadi et al., 2017; Sime et al., 2020a; Tesfay et al., 2021). The system that was installed was a batch digester unit, in which all of the raw materials (water and waste materials) were added simultaneously, allowed to break down for three to four weeks, and then the gas and bio-slurry were removed simultaneously (Abadi et al., 2017; Sime et al., 2020a; Tesfay et al., 2021). This technology's defect is that it cannot continuously supply methane gas because continuous slurry feeding was not allowed, which renders it ineffective and unacceptable. However, Ethiopian government agencies and the Food and Agriculture Organization (FAO) have been working for several years to promote and accelerate this type of technology in the country (Smith 2011). FAO introduced two biogas plants as pilot projects in the 1970s to further promote the technology in Ethiopia (Abadi et al., 2017; Sime et al., 2020a; Tesfay et al., 2021).

4.1.2. From 1980 to 2000

During this time, private and government agencies built over 1000 biogas plants ranging in size from 2.5 to 200 m^3 in various communities across the country (Abadi et al., 2017; Sime et al., 2020a). This implementation period was devoted to demonstrating the efficacy of various biogas technologies (Tesfay et al., 2021). Various models, including fixed dome, Indian floating drum, and bag digesters, were tested during this time period. The cost-benefit analysis of the fixed dome biogas model in Ethiopia shows that its adoption has a significant positive net present value for both households that collect their own energy sources and those that purchase all of their energy sources. However, nearly 60% of the installations were inoperable (Abadi et al., 2017). In general, the fixed dome digester performed poorly and had little success in implementing a market-oriented, self-sustaining biogas program. These shortcomings of the fixed dome digester hampered the spread of biogas technology and discouraged potential users. However, this generation has paved the way for the country's third biogas technology program.

4.1.3. From 2000 to date and National Biogas Program Ethiopia (NBPE)

Ethiopian and German governments collaborated at the end of the 1990s to update Ethiopian biogas technology development. As a result, 60 fixed-dome biogas digesters were built in Addis Ababa and Adama between 1999 and 2002 (Tesfay et al., 2021). This generation's implementation also includes the local construction of the biogas digester and ensuring promotion through successful installation and close proximity. This prompted and motivated the locals to build more biogas plants. Furthermore, according to the SNV report, approximately 150 biogas digesters were built in Tigray in 2005 (Sime et al., 2020b; Tesfay et al., 2021). Ethiopia began implementing a nationally planned biogas program in 2009 (Manon and Bermúdez, 2016; Gezahegn et al., 2018; Gabisa and Gheewala, 2019; Sime et al., 2020a). The National Biogas Program Ethiopia (NBPE) is divided into two phases: Phase 1 and Phase 2. NBPE1 was implemented in four regions (Amhara, Oromia, SNNPR and Tigray) from 2009 to 2013. NBPE2 runs in the same regions from 2014 to 2019.

The NBPE1 and NBPE2 were funded by the Dutch/DGIS and Ethiopian governments, respectively. Additional four regions (Somalia, Benshangule Gumuz, Gambela, and Afar) have been included in the NBPE+ phase (2017-2022). The European Union (EU) and the Ethiopian government provided funding for NBPE+. Promotion and marketing, training, quality management, research and development, monitoring and evaluation, institutional support, extension, and gender mainstreaming are the eight major components of NBPE activities. The overall goal of the NBPEs is to facilitate the expansion of access to modern energy services for rural households and communities through the introduction and development of biogas energy. As a result, the goal of this program is to provide clean and safe energy for cooking and lighting in these communities. This strategy has the potential to replace the use of wood and charcoal, as well as chemical fertilizer, in order to improve agricultural, health, and livelihood conditions in rural areas (Sime et al., 2020b). Furthermore, it aimed to develop commercially viable domestic biogas technology to ensure the country's biogas plants operate continuously. The program's specific goals were to: (1) attract and strengthen institutions and organizations for the development of a national biogas sector; (2) build 14,000 biogas plants in chosen regions over the course of five years; (3) ensure that installed biogas plants are still operating under the NBPE; and (4) maximize the advantages of all biogas plants installed through private sector competition, with the expectation that potential users would gain from lower costs and the better efficiency (H Tesfay et al. 2021).

National Biogas Program Ethiopia Phase one (NBPE1): The five-year pilot implementation phase, which is the first phase of the NBPE, began in 2009. As shown in Table 5, the program has distributed biogas plants in 18 chosen districts (woredas) in the Amhara, SNNP, Oromia, and Tigray regions (Abadi et al. 2017). These districts were chosen based on factors such as the density of people and livestock, the loss of vegetative cover, the level of education and technological adoption in the districts, the availability of relatively well-documented data, and the consumption of woody biomass that exceeds annual production in more than two-thirds of the districts (Manon and Bermúdez 2016; Mengistu et al. 2016; Berhe et al. 2017; Kelebe 2018; Sime et al. 2020b). At the end of phase one implementation, the program had built 8063 biogas plants, representing approximately 57.6 % of the initial planned 14000 installations in 163 sub-districts. The number of installed plants in Amhara (33 sub-districts), SNNP (23 sub-districts), Tigray (29 sub-districts), and Oromia (78 sub-districts) is 1892, 1699, 2001, and 2480, respectively (ABPP, 2017; TRBPCU, 2017), with various biogas digester sizes (4, 6, 8, and 10 m^3) and fixed dome model (Manon and Bermúdez 2016; Mengistu et al. 2016; Berhe et al. 2017; Kelebe 2018; Sime et al. 2020b). Figure 6 depicts the annual installed biogas plants in the four regions. Table 2 shows the districts that have been chosen to implement NBPE1 (H Tesfay et al. 2021).

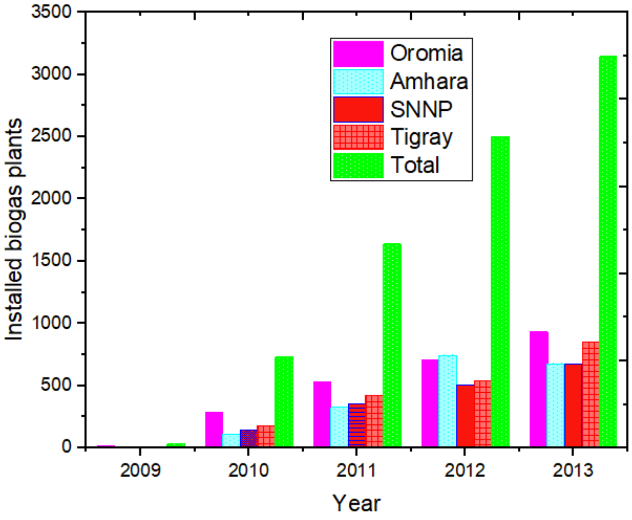

Figure 6: Biogas distribution in Ethiopia during NBPE1 implementation (H Tesfay et al. 2021).

Table 4: Selected woredas to implement NBPE1 (Tesfay et al. 2021).

Regions	Woredas
Oromia	Ada'a, Dugda Bora, Hetosa, Ambo, Kuyu
Amhara	Bahir Dar Zuria, Dembia, Gonder Zuria, Fogera, Dangla
SNNP	Dale, Mareko, Meskan, Arba Minch Zuria, Derashe Special Woreda
Tigray	Hintalo Wajorat, Raya Azebo, western Tigray

Many factors contribute to the 42.4 % failure to meet the NBPE1 target (Manon and Bermúdez, 2016; Mengistu et al., 2016; Berhe et al., 2017; Kelebe, 2018; Sime et al., 2020b). This includes: (1) rising construction material costs, which raise the per digester cost, (2) inadequate or lack of skilled labor and expert's (3) low commitment of stakeholders at the regional level and lack of credit facilities in some regions because the beneficial are not financially well organized, (4) inadequate follow-up service after installation and commissioning, (5) the technology's application is limited to lighting and light cooking and (6) available alternative energy sources to meet their energy needs (Manon and Bermúdez, 2016; Mengistu et al., 2016; Berhe et al., 2017; Kelebe, 2018; Sime et al., 2020b).

National Biogas Program Ethiopia (NBPE2)-Phase two: The second phase (2014-2019) is known as the scale up program, and it aims to spread biogas by incorporating the lessons learned during the first phase. Specific goals for NBPE2 include: (1) scaling up the distribution of 20,000 biogas digesters, (2) scaling up the distribution of biogas appliances for household cooking, (3) pilot installation of larger size digesters, (4) ensuring long-term sustainability of biogas as a renewable energy, and (5) participation of alternative implementing partners and private microfinance institutions (Manon and Bermúdez, 2016; Mengistu et al., 2016; Berhe et al., 2017; Kelebe, 2018; Sime et al., 2020b). During this phase, the program concentrated on the four regions chosen in phase one. From 2014 to 2016, the total number of biogas plants installed in the four regions is shown in Figure 7. Total biogas installations in the four regions were 7330 in these three years, with an annual average of 2443 plants. It will be interesting to see if this trend continues into 2019.

NBPE2 has achieved approximately 73% of the target number of installations. This would be an improvement over the phase one achievement rate (Sime et al., 2020a).

A National Biogas Dissemination Scale-up Program (NBPE+) is currently being introduced by the NBPE, which will continue to 2022 and covers all regional states of the country (Sime et al., 2020b).

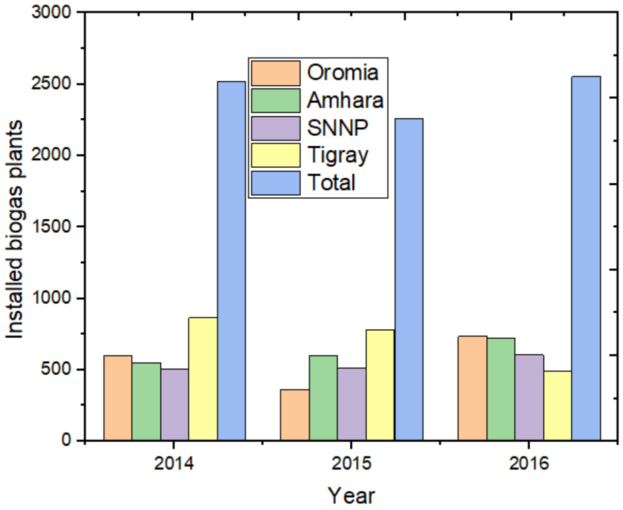

Figure 2: Installed biogas plants between 2014 and 2016.

4.2. Current Status of Biogas Technology in Ethiopia

The number of digesters has significantly increased during Phases I and II of the National Biogas Program, particularly in the four regions that were chosen to implement NBPE. 15,403 digesters have been installed overall during this time, which is about 45.3% of the target (34 000) for the two NBPE phases. In Ethiopia, biogas technology is primarily used for lighting and cooking. About 43% of digester owners use biogas for both lighting and cooking, compared to 10.8% and 3.2% who use it exclusively for cooking and lighting, respectively. On the other hand, incomplete installation and technical issues with the biogas plant have prevented 43% of biogas adopters from using it (Berhe et al., 2017). Table 6 displays the cumulative size of biogas installation and distribution in Ethiopia. The efforts to install bio-digesters in the remaining regions of the country were extremely minimal in comparison to the four regions in phases I and II.

According to SNV's baseline study, 6 m^3 and 8 m^3 biogas digester sizes had 68 % and 25% of all cumulative national installations, respectively, of the installations. As can be seen, there were differences in the size distributions between the regions. The least number of biogas digesters of the four common sizes (4 to 10m^3) have been installed across all regions. In a similar vein, biodigesters larger than 10 m3 were not common in all regions, with the exception of Oromiya, which has 67 % of all installations in this size nationwide. It was discovered that different geographical areas had different bio-digester functionality rates. As shown in Figure 8 (Tesfay et al., 2021)., the SNV baseline study estimates that 54 % of the country's biogas digesters are functional.

Slurry feeding issues and technical difficulties were found to be the main barriers, although various researchers gave various explanations for why biogas digesters weren't functional (Seboka, 2019; Marie et al., 2021; Fentie and Sime, 2022; Tekle and Sime, 2022). The irregularity of feeding, overfeeding, and insufficient initial feeding are the causes of the feeding issues. Technical issues are also classified as issues with the construction process, such as digester technical faults like a cracked dome, a drainage issue, or an incomplete foundation. According to NBPE+ (2018), additional reasons for non-functionality include: (i) lack of spare parts or accessories, (ii) a water supply issue, (iii) relocation of users or due to an owner's passing, (iv) the sale of the owner's cattle, and (v) promotion issues are just a few examples.

5. Challenges to Biogas Development in Ethiopia

In much of rural Ethiopia, access to modern forms of energy is irregular or non-existent. As a result, the population relies heavily on a limited and rapidly diminishing supply of solid fuels like as wood and charcoal for cooking and lighting. Additionally, dung and crop waste are being used as substitute fuels, when they may be better utilised to improve soil nutrients and contribute positively to agricultural production. The broad use of biogas technology and bio-digester functionality is constrained by issues such as economic instability, a lack of technical skills, poverty and illiteracy, societal challenges, and institutional constraints (Mukumba et al., 2016). These are discussed in greater detail below.

Table 5: Installation of biogas digesters in Ethiopia, until March 2017 (H Tesfay et al. 2021).

Size	Oromia	Tigray	Amhara	SNNP	Somalia	Benshangule Gumuz	gambela	Afar	Total
4 m^3	97	-	112	17				1	227
6 m^3	2059	4146	1933	2542		10	7	-	10,697
8 m^3	1400	20	1771	747	15			-	3953
10 m^3	577	44	122	118				-	861
Total	4133	4210	3938	3424		10	7	1	15,738

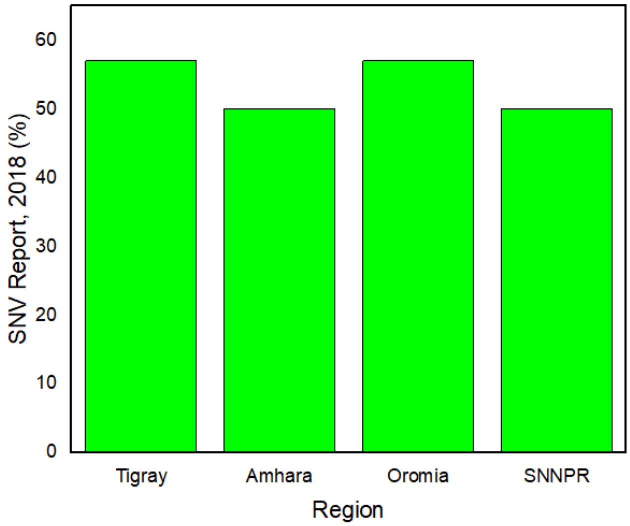

Figure 3: Biogas digester functionality percentage of regions (H Tesfay et al. 2021).

5.1. Expensive Initial Investment in Biogas Digesters

Although biogas technology has the potential to meet Ethiopia's energy needs, particularly those of rural residents, the design and installation of digesters are costly. The initial investment cost is a significant barrier to biogas uptake in Ethiopia, regardless of government support initiatives for renewable energy technologies. For example, the cost of installing an 8 m^3 fixed dome digester is at least 570 USD. However, the government and donations cover approximately 40% of this expense. Additionally, labor is required for daily operation, digester maintenance, supervision, slurry feeding, storage, and disposal. The availability of this labor decides whether or not the digester will operate at full capacity. Daily biogas requirements increase in direct proportion to family size, and as a result, the expense increases as well. Reduced installation costs without sacrificing quality or performance could make bio-digesters more accessible to users (Rupf et al., 2015; Mukumba et al., 2016; Nevzorova and Kutcherov, 2019).

5.2. Biogas Substrates Availability

In rural Ethiopia, cow manure is the primary biogas substrate. For long-term functioning, the amount of substrate entering the digesters should be stable. Biogas digesters are established under the assumption of a steady daily or weekly supply of substrate. Numerous methane digesters fail owing to a lack of substrate and inconsistency in feeding due to the scarcity of manure. Collecting dung is difficult, especially when combined with water to dilute the substrate. Additionally, healthy cattle nutrition is lacking in order to obtain nutritious cow manure for biogas production. To many farmers, the use of other agricultural waste products as substrates for digesters, such as human excreta, poultry dung, pig manure, donkey dung, and garden wastes, is inadequate. As a result, many biogas digesters remain underfed, resulting in the inability to produce methane.

5.3. Lack of research on biogas technology

Ethiopia has a lack of biogas technology research, despite the fact that the country has installed a large number of digesters. There is no data available on the amount of methane produced by installed biogas digesters or on methods for enhancing the quality of the methane. Often, data collection on failing digesters is impeded by certain techniques. Additionally, biogas specialists' research on biogas technology is limited by a lack of funding, which has a detrimental impact on biogas dissemination programmes. Additional research is required to determine the best methods for utilising the biogas from the activated sewage treatment works for the benefit of the country's residents.

5.4.Public Awareness Campaign

Education is one of the most significant impediments to the advancement of biogas technology in developing country, particularly Ethiopia. It is critical to educate the community about the economic, social, health, and environmental benefits of biogas technology in order to establish a successful and sustainable biogas system. Rural communities in the country require proper education to understand the value of biogas energy in comparison to other energy sources. Additionally, there is no biogas technology instruction in primary, secondary, or tertiary schools, and as a result, many rural people are unaware of the social and economic benefits of this new technology and continue to use firewood even when biogas digesters are accessible.

5.5.**Inadequate Construction and Maintenance** Expertise

Inadequate skills for biogas digester building and maintenance is another impediment to the spread of biogas technology in the country. There are few or no technical or vocational schools or colleges that teach students how to install and maintain biogas digesters. Numerous biogas initiatives in the country have failed owing to a lack of effective management as a result of a lack of education.

5.6.Biogas has a low efficiency

Biogas is inefficient as a fuel when compared to fossil fuels such as diesel and petrol. The methods to improve its efficiency so as to run internal combustion engines are lacking. Numerous biogas digesters have been closed due to farmers' lack of experience and cooperation from biogas professionals in optimising biogas's calorific value.

5.7.Minimal Biogasa Application

The amount of substrate available to a digester dictates its size. The digesters constructed in various rural villages have not been sized according to substrate availability. The digesters are identical in size regardless of the substrates available to each family. Although the digesters' sizes should fluctuate according on substrate availability, this is not the case. These digesters are frequently malnourished. In general, a household with two cows may operate a 4 m^3 digester; a home with four cows can operate a 6 m^3 digester; and a household with six cows can operate an 8 m^3 digester (Mukumba et al. 2016).

5.8.Bio-slurry composition and management

Bio-slurry as an organic fertiliser is environmentally safe, contains no toxins or irritants, and may easily replace chemical fertilisers. Bio-slurry is a 100% organic fertiliser most ideal for organic farming. Additionally, the lack of attention paid to the biogas technology's bioslurry aspects was due to the Ministry of Agriculture's minimal involvement. The primary technical issue with bio-slurry management was the outflow of bio-slurry prior to fermentation, the backflow of bio-slurry into digesters, and the vulnerability of bio-slurry pits to flooding during periods of heavy rain. As a result of outflow, there is a risk to health from the foul odours generated during the preparation, transportation, and application of bio-slurry.

Due to insufficient training, user households lacked the necessary technical abilities for preparing and using bio-slurry. The other difficulty was that the rate of bio-slurry application per hectare for various crops had never been documented in Ethiopia, which could have boosted the bio-reputation slurry's and expanded its use in crop production. Additionally, there is a need to campaign for the promotion of biogas's numerous uses beyond cooking and lighting, such as an integrated farming method that incorporates biogas and bio-slurry.

6. Solutions to Biogas Challenges

6.1.Extensive Biogas Research

The National Biogas Programme was launched in 2009 with the goal of establishing a commercially sustainable domestic biogas sector. The Ethiopian Government, in partnership with the Netherlands Development Organization, designed the project, which is coordinated by the Ministry of Water and Energy (SNV). The government should develop training institutes in each region to educate citizens about biogas technology. Extensive research on biogas technology should be conducted, focusing on the following areas: biogas technology constraints in Ethiopia, new biogas designs, model equations for optimum methane yield, techno-economic analysis of rural biogas digesters, prefeasibility and feasibility studies of urban biogas digesters, replacing firewood with biogas for cooking and in electricity generation in rural areas, most suitable inoculums for biogas production, and biogas as a fuel source for power generation. In the country, research on biomass as a source of energy is still in its infancy. At the moment, the government relies heavily on research conducted outside of Africa. When considering the country's present energy needs, new understanding in biogas technology is required.

6.2.Adequate Biogas User Education

To minimize biogas digester failures, the government, non-governmental groups, and biogas installers should train biogas users on feeding and maintaining biogas digesters (Mukumba et al., 2016). Many rural populations who rely on firewood have a limited understanding of the value of biogas as a source of energy, owing to the fact that they have an alternative source of energy. Biogas digesters are constructed in many rural communities to produce biogas for heating and cooking needs, but not for electricity generation or transportation. Through government backing, biogas installers and specialists must train biogas users on the handling of animal wastes, feeding, cleaning, the quantity of water to add to manure, and measures to minimize souring of the biogas digesters. The installation of biogas digesters in remote communities is perceived by biogas consumers as a research endeavor, not a community activity. Thus, biogas users require adequate education to develop a sense of ownership over biogas projects in order to improve their economic, social, and health conditions.

6.3.Substrates Co-Digestion

Numerous digesters installed in rural Ethiopian communities employ cow manure as a substrate for biogas production. Biogas produced from cow manure is extremely low in comparison to other wastes. Wastes are not co-digested, resulting in minimal biogas yields. Co-digestion of organic wastes requires the incorporation of a variety of substrates in variable amounts (Mukumba et al. 2016). Co-digestion is essential to maximize biogas production by promoting ammonia elimination during digestion. The mixing of multiple wastes benefits the anaerobic digestion process because it increases methane yield, improves stability, and facilitates waste management. Additionally, such a system is more economically viable because it consolidates multiple streams into a single facility. When food waste and toilet waste are co-digested, the toilet waste's low carbon: nitrogen (C/N) ratio and biodegradability content are compensated for by the food waste's high values for those two parameters. Thus, the major issue of ammonia toxicity caused by a low carbon/nitrogen ratio is avoided, and the low biogas output caused by a low biodegradable matter content is increased. As a result, co-digestion of wastes improves the quality of biogas.

6.4.Enhancing Biogas's Calorific Value

To boost biogas's calorific value, it should be purified and upgraded to eliminate carbon dioxide, hydrogen sulphide, and water vapour. The biogas scrubbing unit will be divided into three subsystems: CO_2 separation, H_2S separation, and moisture separation. Purified biogas produced by the scrubbing units has roughly 95% methane, compared to biogas produced directly from cow dung-fed biogas digesters, which contains approximately 55% methane. The biogas, now referred to as bio-methane, has a high heating value (Figure 9).

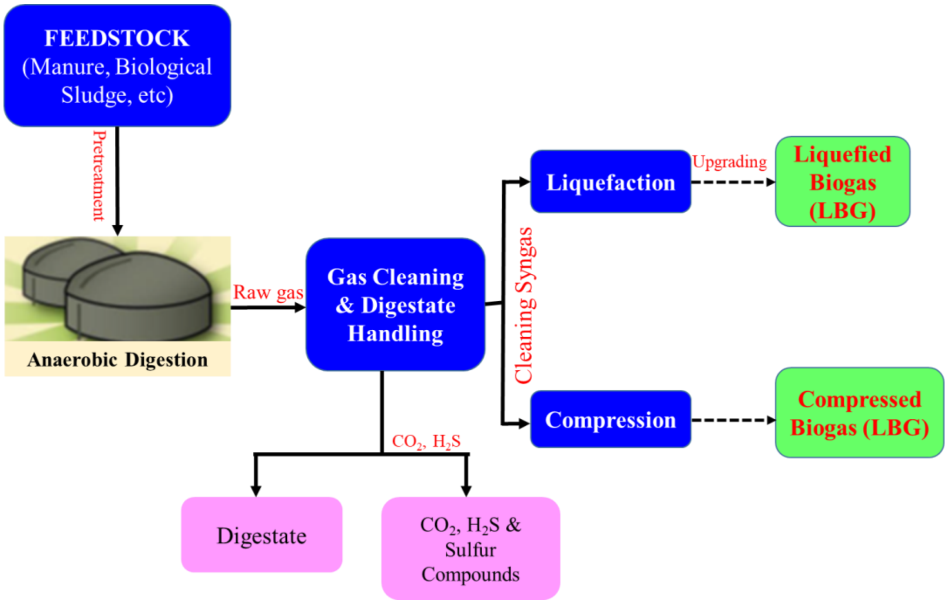

Figure 4: Biomethane versus Anaerobic digestion.

6.5.Designing Digesters Depending on the Substrates Available

The biogas digesters that will be constructed in various communities should be developed in accordance with the substrate availability for each family. Oversized biogas digesters result in the failure of the digester due to insufficient feed. The digester's size is also determined by the retention duration and temperature (Mukumba et al., 2020).

7. Conclusion

For many years, humans have used biomass energy as a source of fuel. It is considered a renewable energy source because, unlike carbon-emitting fossil fuels, it is a carbon-neutral energy source. This is why there are breakthroughs and advancements in biomass energy, particularly in the current use of biomass as a source of energy in many countries. It is an important source of energy, accounting for more than 80% of Ethiopia's energy consumption. Despite the fact that Ethiopia has a large potential for various alternative energy sources, electricity access is limited because the majority of the population lives in rural areas due to the country's dispersed population distribution. Furthermore, because national grids were located far from rural residents, the majority of rural residents lacked daily access to electricity. The majority of rural societies rely on free woody biomass, crop residues, and livestock dung collection. As a result, they rely on traditional biomass energy sources such as burning wood, dung, and agricultural waste for cooking, heating, and lighting. Currently, energy demand is increasing, while power generation supply should be balanced with demand.

Therefore, this review describes the current challenges and potential solutions to the widespread use of biogas as a source of energy in Ethiopia. The country's biogas technology expansion faces a number of obstacles, including a high initial investment cost for biogas digesters, insufficient skills for biogas digester building and maintenance, and low biogas efficiency. Additionally, it was noted that a lack of research on biogas technology is impeding the country's biogas digester expansion. It may be stated that the country's installed biogas digesters should be sized appropriately for the substrate available. Additionally, the calorific value of the biogas should be increased by conversion to bio-methane, which can be utilized to power internal combustion engines and generator sets. Additionally, community-based training about biogas production and use should be begun to minimize biogas digester failures. There is a need to completely engage and accelerate the spread of biogas digesters in the country by developing innovative digester designs and giving enough information to biogas users on biogas usage, maintenance, handling, and co-digestion optimization. We certainly hope that the contributions we have made to this review will be extremely helpful to researchers, educators, decision-makers, working professionals, senior undergraduate and graduate students, and other people who are interested in pollution remediation and energy production and storage using renewable and affordable bio resources.

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