Renewable Energy from Agricultural Waste: A Review of Biogas Potential for Sustainable Energy Generation in Nigeria's Rural Agricultural Communities

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ABSTRACT

Globally, fossil fuels dominate energy generation. As the world shifts towards sustainable processes and a circular economy, seeking renewable energy alternatives is crucial. Nigeria's agricultural sector produces large amounts of biodegradable waste daily, with an estimated 12.06 Mt annual agro-waste production. This offers potential for bioenergy generation in agricultural communities, especially at the rural level. Biogas plants employ anaerobic digestion, which enables microorganisms to break down large organic molecules into biogas. This review examines the trend of biogas use in Nigeria, revealing that while much research has been conducted on biogas production over the past two decades, much progress has not been made in implementing it on a large scale due to financial barriers, lack of awareness, policy support, technical expertise, etc. Nevertheless, the progress made in the small-scale implementation of biogas plants shows their potential for use in rural agriculture. The proposed solutions seek to aid rural farmers in affording an environment-friendly, off-grid energy supply for production.

Keywords: Biogas, Anaerobic digestion, rural agriculture, sustainability, circular economy, bioeconomy.

1. INTRODUCTION

Energy supply today is very crucial. Fossil fuels have dominated the energy supply for many domestic, agricultural, and industrial purposes. However, we see two major setbacks in their use: their finite supply and ecological impact. The supply of fossil fuels is limited and not renewable. Numerous studies provide convincing evidence of the depletion of fossil fuel supplies [1]. Precisely, the global supply of fossil fuels is projected to last for up to 25 years, according to numerous studies; as a result, alternative energy sources like renewable energy are required [2].

Furthermore, the annual production of carbon dioxide (CO2) and greenhouse gases (GHGs) from the combustion of fossil fuels is around 21.3 billion tonnes. Naturally occurring processes are said to be able to eliminate only half of it. Thus, the annual increase in CO2 in the atmosphere is 10.65 billion tonnes [3]. Consequently, there is a need to develop new approaches to meeting the energy demands of the society sustainably. Beyond these, however, developing alternative energy sources for use in rural areas is expedient, providing solutions to the challenge of limited access to conventional energy options [4]. This is very applicable in the area of rural agriculture where energy is required for heating and electricity generation [5] among others. Rural communities frequently struggle to access reliable energy sources, making them very reliant on energy sources like firewood and fossil fuels. These contribute to air pollution, deforestation, greenhouse gas emissions, and environmentally unsustainable practices [6]. By utilizing organic resources that are readily available locally, lowering waste disposal concerns, and offering rural communities a decentralized energy solution, biogas production from biowaste presents a competitive alternative [4]. Biogas is obtained from the process of Anaerobic Digestion (AD). It is the result of a biologically facilitated process. Methane (CH_4) makes up roughly 50–70% of biogas, while carbon dioxide (CO_2) makes up 30–50%. The amount of each component in biogas varies mostly depending on the kind of substrate [7]. This review seeks to analyze the potential of biogas use for sustainable energy generation in Nigeria's rural agricultural sector. The process of Anaerobic Digestion and the technologies that can be implemented in biogas plants at the rural level are discussed. Furthermore, the existing trends in biogas use in Nigeria and other world nations are reviewed. The possible barriers to implementing biogas technologies for rural agriculture are also discussed and solutions are proposed.

2. THE ANAEROBIC DIGESTION PROCESS

Biogas production is achieved through the process of Anaerobic Digestion (AD). AD takes place when methanogens or anaerobic microorganisms break down organic matter in a closed system which could include a bioreactor, a biodigester, or an anaerobic digester [8]. Several microbiological, biochemical, and physico-chemical processes are involved in the AD process, which is considered the most environmentally sustainable way to manage biowaste. Also, the substrate selection for an AD process can significantly impact the rate of biogas production and production efficiency [9]. Anaerobic Digestion involves four phases where different groups of microorganisms work in coordination to bring about digestion [9]. They are outlined as follows:

2.1 The Hydrolysis Phase - This is the initial phase of the AD process. It involves the conversion of organic biomass such as carbohydrates, lipids, proteins, and nucleic acids into simpler monomers and oligomers, which include simple sugars, amino acids, and fatty acids, by the action of hydrolytic bacteria which secrete extracellular enzymes [4, 10].

2.2 The Acidogenesis phase - In this phase, acidogenic bacteria act on the products of the hydrolysis phase, breaking them down into methanogenic substrates. Simple sugars, fatty acids, and amino acids are converted into acetate, hydrogen, and CO_2 as well as volatile fatty acids and alcohols [11, 10].

2.3 The Acetogenesis phase - In this phase, substrates from the acidogenesis phase are converted by acetogenic bacteria into Hydrogen, CO_2, and acetate, resulting in a drop in the pH of the aqueous medium [12, 13].

2.4 The Methanogenesis phase - In the methanogenesis phase, methanogens are employed to convert hydrogen and CO_2 into methane. This they do by the reduction of CO_2 and oxidation of Hydrogen. Acetolactic methanogens also produce methane from acetate [14]. Methanogenesis produces about 70% of the methane in an Anaerobic Digestion process, thus playing an important role [15]. Figure 1 gives a summary of the Anaerobic Digestion process.

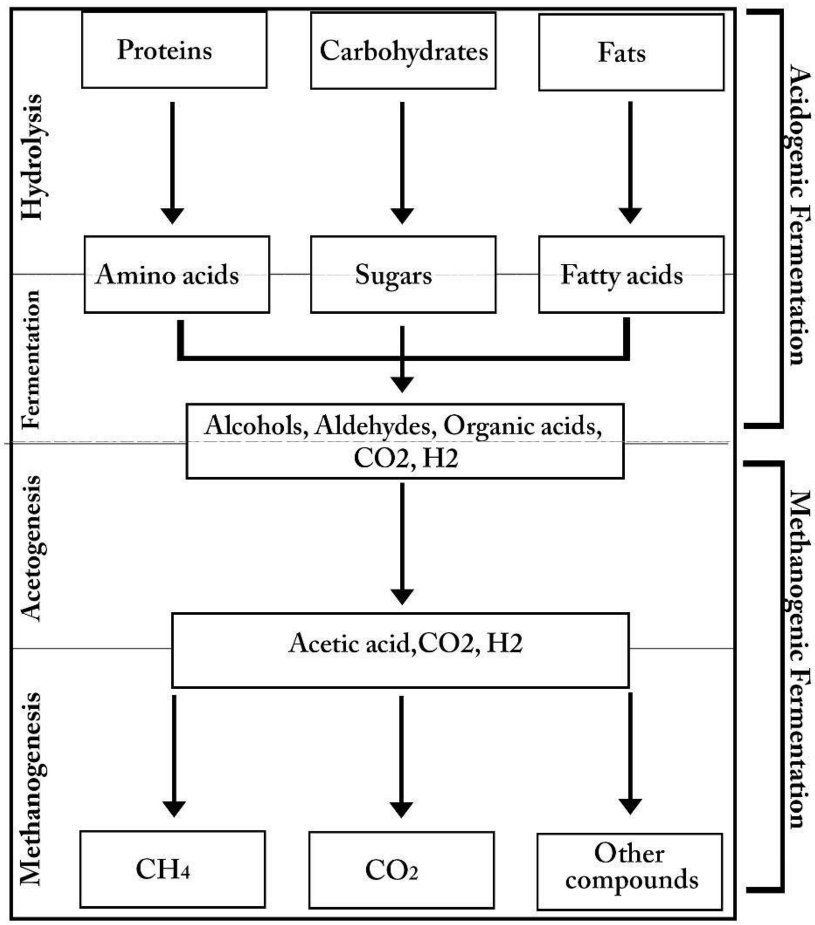

Fig. 1. A schematic of the Anaerobic Digestion process [9].

3. BIOGAS PLANTS TECHNOLOGY

Biogas plants thrive on the Anaerobic Digestion process to obtain renewable energy from organic waste in the form of biogas [9]. According to [16], a biogas digester is a sealed, airtight vessel that is used to improve the anaerobic digestion of biodegradable waste, such as sludge, black water, and animal dung, and to collect the biogas that is created. They include batch systems, covered lagoons, continuous stirred tank reactors, and plug flow digesters [17, 18]. Agricultural biogas plants are suited for agricultural feedstock [9]. In our consideration of the application of biogas in rural agriculture, we account for different sizes that agricultural plants can take which include family-scale biogas plants; small, medium, or large farm-scale biogas plants [10]. In their work on digesters, [19] classified biogas digesters types based on operational mode and based on scale. Operationally, biogas digesters can be classified into:

(a) Passive systems: involves including a biogas recovery system to an existing waste treatment system with minimal or no control of the anaerobic digestion.

(b) Low rate systems: here the solid retention time (SRT) is equal to the hydraulic retention time (HRT). The source of biogas forming microorganisms is the waste flowing in.

(c) High rate systems: in these, the methane forming organisms are held and retained in the digester to improve digestion efficiency.

They can also be classified according to scale as:
(a) Domestic or residential digesters: They have a power capacity < 25kw. They are used for domestic applications in rural residential areas.
(b) Small and commercial medium scale digesters: They have a power capacity between 25 to 250kw. They are used for large scale energy applications such as heating and electricity generation.
The design of biogas plants involves analysing the substrates, the demands of the production, and the operating conditions for production [20, 9]. Concisely, the principle of biogas plants involves the entry of feedstock either directly or after a mixing stage, the retention of substrate, collection of biogas, and then its exit through an outlet for use [21].

3.1 Types of Biogas Designs

[19] in a review on biogas digester types in South Africa outlined the different types of biogas digesters used in agricultural and industrial applications. This corresponds to small and medium-scale digesters earlier stated and are outlined below:
3.1.1 The plug flow digester - The substrate flows in as a plug and there is no longitudinal mixing throughout the process. It involves the use of a long and narrow tank whose length-to-width ratio averages 5:1 [22]. The digestate moves towards the tank's exit at the opposite end as new substrate is fed from the input. Because of the inclined location, acidogenesis and methanogenesis can be separated longitudinally, resulting in a two-phase system [19].
3.1.2 The lagoon digester - A lagoon is a two-cell waste treatment and storage system [23]. The first cell is covered while the second is left uncovered. They work harmoniously for the effective functioning of the system. The first cell contains biodegradable waste while the second contains liquid that alternates in its level to create storage space. As the anaerobic breakdown of the waste proceeds, the gas generated is confined beneath the impermeable cover. Lagoon digesters are inexpensive, very successful in reducing odors even in cold areas, and function best with liquid manures that contain less than 2% total solids [19].
3.1.3 Complete mix digester - An active mass of anaerobic microbes is combined with heated substrate in a tank to create a complete mix digester. When the digester volume is displaced by the incoming feed, the same volume of liquid exits. Along with the displaced digestate, the methane-forming bacteria exit the digester. It allows for the continuous or intermittent mixing of the digester [19].
3.1.4 Fixed film digester -The fixed-film digester is made out of a plastic media-filled tank. A thin coating of anaerobic bacteria known as a "bio-film" is supported by the medium. Biogas is created as the waste manure flows through the medium [19].

4. CURRENT TRENDS IN BIOGAS IMPLEMENTATION IN NIGERIA

Anaerobic waste digestion has garnered significant global attention within the past 20 years. This is because it creates biogas, a renewable energy source that is relatively simple to adopt, requires little energy to operate, and offers solutions to waste management issues [24]. In Nigeria, biogas production has advanced significantly due to the nation's initiatives towards sustainable energy generation and waste management [25, 26]. There are several biogas plants in Nigeria, varying in scale and capacity and positioned in areas with significant waste production [25, 27]. Small-scale biogas plants are used in rural areas to meet the energy demands and waste management needs [28]. In their research on the current situation of anaerobic digestion for biogas production in Nigeria, [28] outlined several biogas projects that have been executed within the country. Some of them are outlined below:
1. A biogas plant capable of converting organic waste using four 5000-liter digester tanks was launched in Ikorodu mini abattoir, Lagos. This initiative, launched by the Lagos state government, Friends of the Environment (FOTE), and HIS biogas, uses organic waste and wastewater from the abattoir to power the abattoir for about six hours daily.

2. Avenam, a Lagos-based company, has also set up several biogas plants in parts of the country in conjunction with other stakeholders. These find various applications and are outlined below:

(i) A biogas plant using cassava and cow dung to produce biogas for electricity generation in Ibadan, Oyo State.

(ii) A biogas plant situated in Ogun state that produces biogas from poultry waste for electricity generation.

3. The International Institute for Tropical Agriculture (IITA), Ibadan in 2022 launched a biogas plant that uses anaerobic digestion to generate biogas for cooking purposes.

These are just a few among several projects that exist. Unfortunately, it is worth noting that Nigeria has not been successful at implementing the production of biogas on a large scale. [29] in a research on biogas and biofertilizer production in Nigeria stated that biogas technology in Nigeria had been limited to institutional research work and pilot projects due to a lack of knowledge, research conducted at universities that are sometimes seen too scholarly, a lack of political will, and an inadequate coordinating framework. [30] stated that although the raw materials were widely available in Nigeria, the necessary equipment and expertise to generate energy from biomass on a large scale were lacking. [28] stated that agricultural firms and households own the majority of biogas plants in the country. While this reflects a lag in the country's adoption of biogas on a large scale as a renewable energy intervention, the progress in the implementation of biogas technologies on a small scale shows the feasibility of its use as a renewable energy intervention for rural agricultural practice. Indeed, some work has been done showing the potential of biogas use in rural agriculture. In a research by the National Center for Energy Research and Development, University of Nigeria, Nsukka, [31] characterized a fixed dome biogas plant through the anaerobic digestion of cow dung, a common agricultural waste product, to produce biogas that was used to power cooking operations. This small-scale application of cow dung for heating can be developed and implemented for heating operations in rural agriculture. In a report by [32], energy enthusiast Fatima Ademo embarked on a project to set up an off-grid biogas plant in the Rije community of Abuja, Nigeria. This plant was to utilize animal waste such as chicken or cow manure to produce clean and sustainable energy for agricultural communities. Despite being successful, its operation was halted due to the lack of supply of organic substrate for the conversion process. Nevertheless, the biogas plant at Rije serves as an example of how biogas can be implemented in rural agriculture in Nigeria.

Amidst the inconsistencies in Nigeria's biogas production, the report shows that Nigeria's waste generation rate demonstrates great potential for biogas production. For example, [29] at the time of their research employed mathematical computation to estimate that Nigeria produces 542.5 million tonnes of selected organic waste annually, which has an annual biogas yield potential of 25.53 billion m3. They concluded that this biogas yield had the potential to replace the use of coal and kerosene for domestic purposes and reduce wood fuel use by 66%. He also reported the biogas potential from different biomass in Nigeria as represented in Figure 2. Figure 3 also shows how different waste types perform when analyzed for their biogas production prospects.

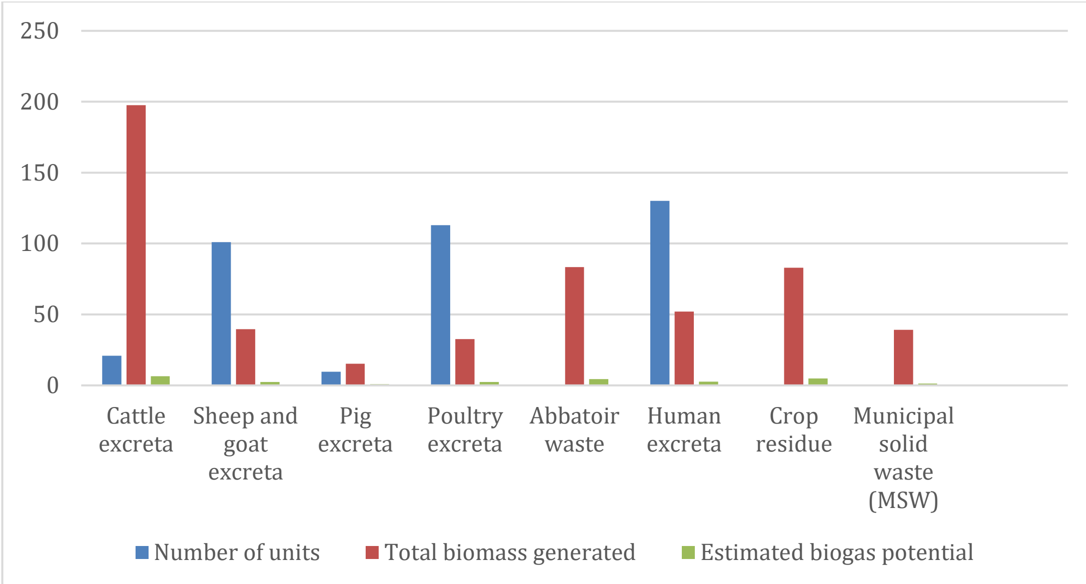

Figure 2. Different biomass generated in Nigeria showing the potential of biogas derivable [29]

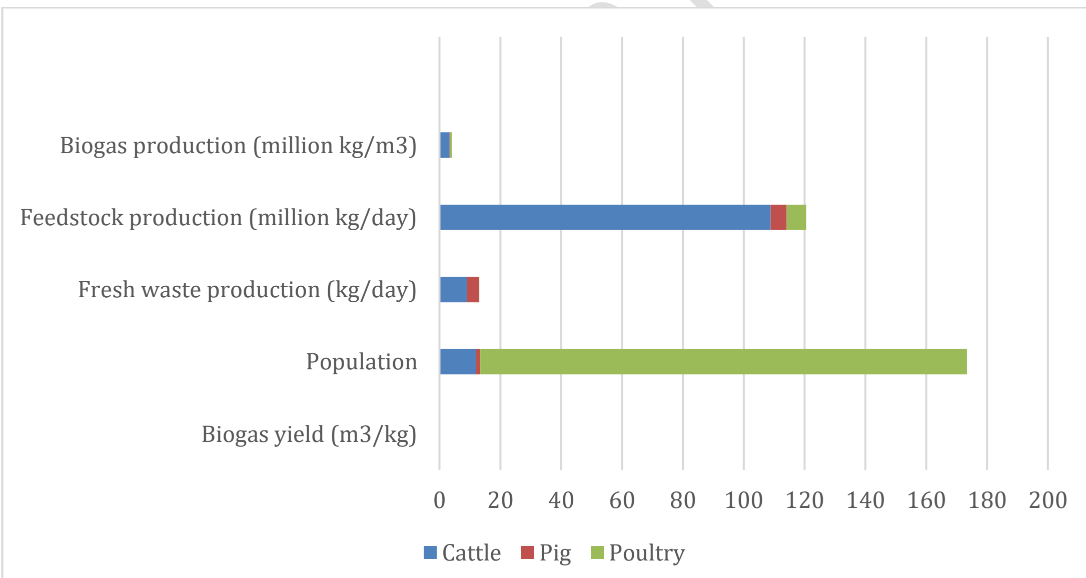

Figure 3. Biogas production prospects from various waste types in Nigeria [33]

[30] stated that 227500 tons of fresh animal waste were produced in Nigeria daily of which 1kg had a biogas production capacity of 0.03m3. He further stated that Nigeria had a 6.8 million m3 biogas production potential from the waste produced. More recently, [34] by analyzing the annual agro-waste generation in Nigeria farms from different crops estimated that 12.06 Mt of agro-waste was produced annually.

5. GLOBAL BIOGAS TRENDS

The production of biogas has been increasingly adopted in recent times for its benefits to the environment and its usefulness for energy generation from waste [35]. We will be examining the cases of the European Union (and the UK), China, the United States, and India.

5.1 China -The use of biogas in China has been mostly for small-scale applications with relatively lesser commercialization [36]. Notably, China currently has the largest number of biogas plants in operation with up to 40 million plants, the majority of which are used for household applications. Numerous Chinese farms also possess biogas plants, using animal manure and household organic waste as feedstock. Biogas, in the above cases, is employed for heating, cooking, and also lighting operations [9]. Table 1 below gives a picture of biogas production in China, highlighting cases for agricultural based substrates.

Table 1. Production of biogas, biogas production substrates, and biogas potential in China [37].

Biowaste Substrates	**Resources available (10^8t)**	**Moisture content (%)**	**Biogas production potential (m^3/t wet base)**	**Total biogas production potential (10^8 m^3)**	**Current potential utilization (%)**	**Biogas production ($10^8 m^3$)**
			Agriculture			
Manure	17[a]	70-80	60	1020	15	153
Straw	6.7[b]	6-12	200	1340	10	134
Fruit and vegetable waste	2.5[b]	80-90	30	75	10	7.5
Total	**26.2**			**2435**		**294.5**
			City			
Municipal sludge	0.5[c]	80	40	20	20	4
Kitchen waste	1.8[d]	75-85	70	126	50	63
Domestic waste (landfill)	1.1[d]	50	120	132	40	53
Total	**3.4**			**278**		**120**

5.2 India -Globally, the microscale biogas industry has been dominated by China and India [38]. For context, the Biogas Development Programme in India has installed almost five million family biogas systems. 400 off-grid biogas power plants function alongside these, with a combined power output capacity of about 5.5 MW [39]. However, compared to other applications, a relatively lesser proportion of biogas produced is used for agricultural applications in both China and India [40]. This is represented in Figure 4.

5.3 United States -The global production of biogas is mostly concentrated in the United States and the EU [41]. With around 90% of anaerobic digestion facilities installed in recent years, and the majority of them (86%) using dairy manure as the primary raw material, anaerobic digestion is well-established in the United States when it comes to employing manure sludge as a substrate [42, 43]. According to estimates, biogas in the US has an annual production potential of 18.5 billion m3, of which 7.3 billion m3 comes from manure, 8.0 billion m3 comes from landfills, and 3.2 billion m3 comes from WWTPs [44].

Figure 4. Main uses of biogases for selected countries and regions, 2021 [40]

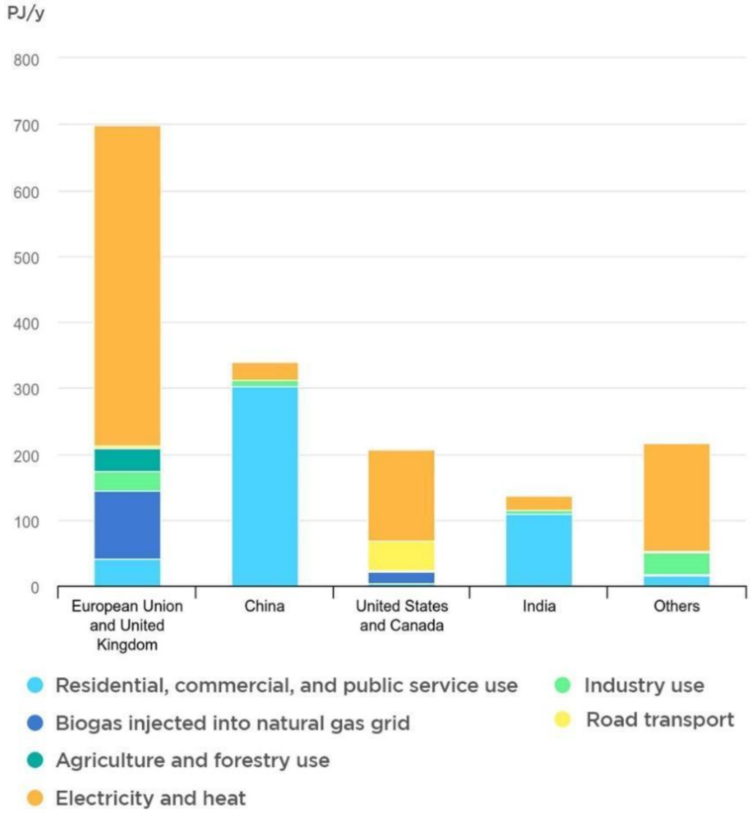

Figure 4. Main uses of biogases for selected countries and regions, 2021 [40]

5.4 Europe -The EU's energy and climate policies, along with the establishment of various programs of support to stimulate the use of renewable resources, have encouraged the development of biogas production in Europe [45]. The nations Germany, United Kingdom, Italy, Czech Republic, and France are at the forefront of biogas production in the EU. Table 2 gives a representation of the Biogas generated in Germany for the year 2020. This gives insight to the production rate of Biogas available there. Biogas generated in the EU is mostly used for electricity generation [45]. A significant portion of the biogas generated in the EU is used for agricultural applications as seen in Figure 4. Figure 5 also gives a breakdown of the atate of biogas production in Europe for the year 2020.

Table 2. Biogas production statistics in Germany, 2020 [37]

Plant type	**Number of plants**	**Energy production (GWh/yr) (Gross electricity)**	**Energy production (GWh/yr) (Gross heat)**
WWTP	1271b	1600	2400
Bio-Waste	292(142+50)	1000	500
Agricultural	8400c	27800	13600
Biomethane	232	2900	3900
Landfill	280b	300	100
Total	10551	33600	20500

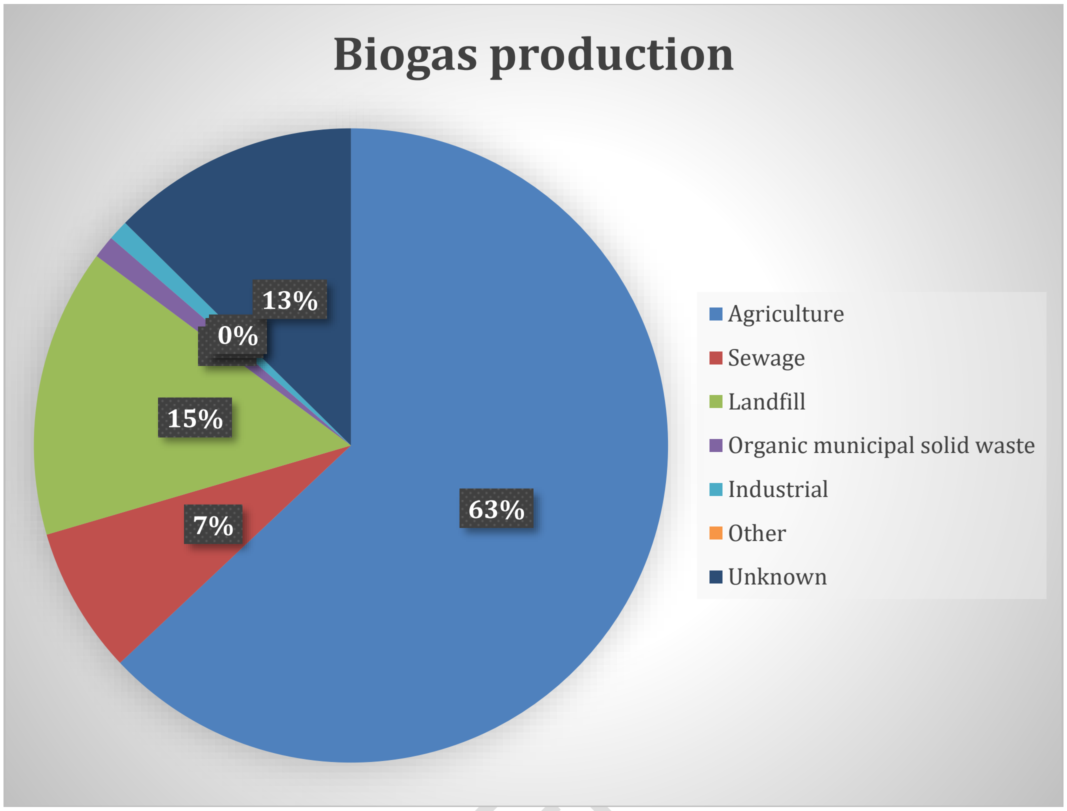

Figure 5.. Production of biogas in Europe in 2020 per plant type in GW/h (EU27 + UK + Switzerland + Norway + Serbia + Iceland) [46]

6. POTENTIAL BARRIERS TO BIOGAS USE IN RURAL AGRICULTURE

Not much progress has been made in the overall implementation of biogas technologies in Nigeria. Several factors responsible for this are enumerated below:

6.1 Lack of sufficient funding -The cost of biogas plant acquisition is huge in terms of operation and maintenance [47]. The income obtainable from subsistence farming, which is largely practiced among rural farmers, is not sufficient for them to acquire biogas plants [24]. This challenge is prohibitive to the implementation of biogas technologies.

6.2 The lack of proper awareness -The lack of adequate strategies for enlightenment on biogas technologies coupled with low education levels among people in rural areas and their lack of access to modern media has led to poor perceptions and attitudes among Nigerians towards biogas technologies [24]. The benefits and prospects of bioenergy technology, namely energy generation and waste management, are not well known to the majority of the farmers and processing industries in Nigeria [47].

6.3 The absence of proper policy and regulatory framework -The lack of legislation, enabling the implementation of clean energy policies has impeded the development of the energy sector in Nigeria [24]. According to [48], properly developed policies are required for bioenergy technology to be properly implemented in any country. However, Nigeria lacks a well-defined bioenergy technology development policy [24].

6.4 Lack of infrastructure and qualified personnel -Nigeria's inadequate transportation infrastructure has the potential to disrupt feedstock supply chains to the operational site of biogas plants [47]. Potential stakeholders may also be discouraged by the lack of qualified technical personnel who are experienced in the design, construction, and management of biogas plants [28].

6.5 Market competition -In rural regions, local biomass sources like firewood and animal dung—which are more affordable and easily accessible—compete with biogas. In urban areas, biogas is competitive with cheap electricity generated by coal and natural gas-fired power plants [24].

7. COUNTERMEASURES TO OVERCOMING THE BARRIERS

7.1 Public awareness creation -Investment and policy development in the biogas sector may be made possible by growing public awareness of the potential benefits of this technology economically and environmentally [43]. This includes enlightening the relevant stakeholders and promoting the value of the technology to them. These stakeholders include producers of biomass feedstock, waste management agencies, the Energy Commission of Nigeria, the Central Bank of Nigeria, Ministries of Power, the environment, and agriculture, etc [49].

7.2 Policy development and implementation -The advancement of AD technology is closely linked to regulations, incentives, and policies in the energy, environmental, and agricultural sectors These policies aim to improve environmental quality, reduce climate change concerns, boost rural economies, and promote energy security [43]. Thus, the development of such policies in Nigeria will aid the adoption of biogas use in rural agriculture. The Nigerian government will also need to ensure that the policies created are implemented [49].

7.3 Financial support structure for local farmers -The provision of funding for AD processes is very key. Upon enlightenment, there is a need for the provision of loan facilities by stakeholders and government incentives to aid farmers in using AD technology. Startups aiming to enter the clean energy industry can receive support from private institutions such as commercial banks, venture capitalists, and private equity financing organizations [49].

8. FUTURE PROSPECTS

The current trend of Biogas use in Nigeria, especially in the rural agricultural sector, reveals that much work still needs to be done in developing Biogas technology in Nigeria. The future holds a lot of prospects and opportunities cutting across different areas of society. According to [50] solving the problems that hinder the implementation of biogas technology could lead to opportunities such as biogas feedstock availability in large amounts and promotion of large-scale agriculture due to favorable climatic conditions, among others. Biomethane generation and the upgrading of biogas present new options for the use of biogas in place of fossil fuels in the transportation sector, removing constraints on the use of heat and enhancing the economics of biogas plants [45]. This can be used in agricultural applications where a higher purity of biogas would be preferred and also for transportation activities where biogas powered vehicles could be used provided that the favorable policies are implemented and the infrastructure also made available.

Biogas can contribute significantly in grid balancing both for electricity and for natural gas use. The development of biogas technology increases the proportion of renewable energy sources in the electricity grid. The combination of biogas plants with solar or wind is already being developed in other countries globally into Hybrid systems [45]. These are future prospects for the Nigerian rural agricultural sector where biogas will be used in grid balancing and for developing hybrid systems that leverage on other cheaply available renewable energy sources and also promote sustainable agriculture.

Also, while anaerobic digestion is a proven technology, there is room for improvement and cost savings through thermophilic processes which improve biological efficiency and biogas yield, dry fermentation, and enhanced biological processes. Furthermore, due to improved pre-treatment technologies (such as hydrolysis, etc.) that aim to increase the biodegradability of feedstock, more feedstock types, particularly those with a high cellulose concentration, may be expected to be utilized. Advances in biogas production can also be achieved through the use of new enzymes and substrates, bacterial strains that are more tolerant to process modifications and feedstock types, and ultrasonic treatment as means of improving the biological digestion process [45]. This is expected to be accompanied with more research in the field of biogas production through biomass valorization, exploring the aforementioned areas in enhancing the production of biogas.

Finally, the development of these technologies can also have a positive benefit to society through the creation of several job opportunities. This would contribute significantly to a reduction in the high unemployment rate seen in the country. It is worth saying, however, that most of these possibilities are only feasible when the right polices are implemented that favor the production and utilization of biogas in Nigeria, especially in its rural agricultural sector.

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