Journal of Engineering Research and Reports

Volume 26, Issue 12, Page 341-367, 2024; Article no.JERR.125184
ISSN: 2582-2926

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

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: https://doi.org/10.9734/jerr/2024/v26i121362

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/125184

Review Article

Received: 08/10/2024
Accepted: 20/12/2024
Published: 26/12/2024

ABSTRACT

The use of fossil fuels dominates energy generation globally. As the world shifts towards developing sustainable processes and a circular economy, seeking renewable energy alternatives is crucial. Nigeria's agricultural sector produces large amounts of biodegradable waste daily with up to 227500 tonnes of animal manure produced per day and up to 84Mt of useful crop residues produced per year. This offers huge 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 potential of biogas production in Nigeria. The technology of biogas production was explained and the trending issue of sustainable

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Cite as: *Godfrey, Okeke Ugochukwu. 2024. "Renewable Energy from Agricultural Waste: Biogas Potential for Sustainable Energy Generation in Nigeria's Rural Agricultural Communities". Journal of Engineering Research and Reports 26 (12):341-67. https://doi.org/10.9734/jerr/2024/v26i121362.*

digestate management was also reviewed. A literature survey revealed that Nigeria has the potential of producing up to 6.8 million m^3/day of biogas from animal waste, and 15.014 billion m^3/year of biogas from crop residues. It also identified that while much research has been conducted on biogas production in Nigeria 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. The absence of effective policies and regulatory frameworks were identified as the major challenge to biogas production in Nigeria. Nevertheless, the progress made in the small-scale implementation of biogas plants shows their potential for use in rural agriculture. Solutions to the barriers were also assessed which, if implemented, will 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

The energy supply today is very crucial. Fossil fuels have dominated the energy supply landscape 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 (Saleem, 2022). Precisely, the global supply of fossil fuels is projected to last up to 25 years, according to numerous studies. Therefore, alternative energy sources like renewable energy are required (Bhatia et al., 2020). The annual production of carbon dioxide (CO_2) 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 CO_2 in the atmosphere is 10.65 billion tonnes (Sarkar et al., 2012). This increase in CO_2 emission leads to increased global warming and ocean acidification, compromising the quality of life on our planet. Therefore, 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 (Akhilesh Kumar Singh et al., 2023). This is very applicable in the area of rural agriculture where energy is required for heating and electricity generation (Shaaban & Petinrin, 2014) 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 (Kasinath et al., 2021). 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 (Akhilesh Kumar Singh et al., 2023). 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 (Angelidaki et al., 2018). Biogas is utilized as a renewable energy source, where it may provide heat for cooking in homes, lighting, and power at the national grid level when it is upgraded to emit less than 5% CO_2 (Mohammed et al., 2022). The use of biogas technology ought to reduce deforestation and the negative environmental impacts associated with it. Biogas technology helps mitigate the issues caused by energy scarcity in rural regions because it uses easily accessible local resources as its substrates (Nzila et al., 2012; Prasad, 2012; Satyanarayan et al., 2008; Walekhwa et al., 2009). By studying deforestation in Africa, (Subedi et al., 2014) estimated that using biogas technology can reduce deforestation caused by the demand for wood, as a source of fuel, and charcoal by 4-26% by 2030, employing cattle dungs as the major substrate for Anaerobic Digestion. Different forms of organic waste are employed in the process of biogas production including animal manure and food waste. Animal waste not only provides a source of energy through AD but the digestate from the process is used as an organic fertilizer for the cultivation of crops (Budiyono et al., 2014; Risberg et al., 2013). The digestate also has a potential for use as an herbicide, pesticide, and cattle feed, as well as for aquatic animals (Ajibola & Junior, 2013). This review seeks to analyze the potential of biogas use in 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 biogas production potential and existing trends in biogas use in Nigeria are reviewed. The possible barriers to implementing biogas technologies for rural agriculture are also discussed as well as solutions to them.

2. BIOGAS TECHNOLOGY, SUSTAINABLE DEVELOPMENT GOALS, AND THE CIRCULAR ECONOMY

The Sustainable Development Goals (SDGs) were set up to address the issues faced by the environment and society as a result of societal evolution. They were adopted in 2015, indicating a shift from the millennium goals. As a result, 193 nations have been given the task of achieving a set 169 targets towards the 17 SDGs by the year 2030 (Ferdeș et al., 2022). Closely associated with sustainable development is the concept of the circular economy. According to (Geissdoerfer et al., 2017), the circular economy is a regenerative system that slows, closes, and narrows material and energy loops to reduce resource input, waste, emissions, and energy leakage. The term "circular economy" is both linguistic and descriptive in its meaning with another term, "the linear economy" meaning the opposite (Murray et al., 2019). The linear economy concerns converting natural resources into waste material (Murray et al., 2019) which in turn contributes to environmental deterioration (Dhungana et al., 2022). The circular economy aims to replace various linear economies. By encouraging the recovery of resources and materials, and reduction in waste generation during production, processing, and consumption, the circular economy aims to reduce environmental damage. Transiting from a linear to a circular economy is essential for diverting value lost in resources, converting them into valuable products and thus fostering sustainable development. The use of AD technologies is a good opportunity to employ the concept of the circular economy (Dhungana et al., 2022). Anaerobic digestion employs organic waste, such as food waste (FW), as raw materials for the generation of biogas. This avoids food wastage and also wastage in the form of land on which food is cultivated, and money put into the cultivation of food crops. Thus, the technology thrives well on the concept of the Circular Economy (Emmanuel et al., 2024). This is also applicable to other forms of organic waste used in Anaerobic Digestion (AD). The process valorizes waste streams from agricultural processes by putting them back into the process cycle, converting them into value products. Fig. 1 gives an illustration of a circular economy design in food production.

The use of AD technologies also fosters the attainment of several of the Sustainable Development Goals (SDGs). Indeed, connections have been shown between the production and utilization of biogas through anaerobic digestion and 15 out of the 17 SDGs (Obaideen et al., 2022). Nevertheless, we are more concerned in this review on the seventh SDG and how the production of biogas contributes towards its attainment. The seventh

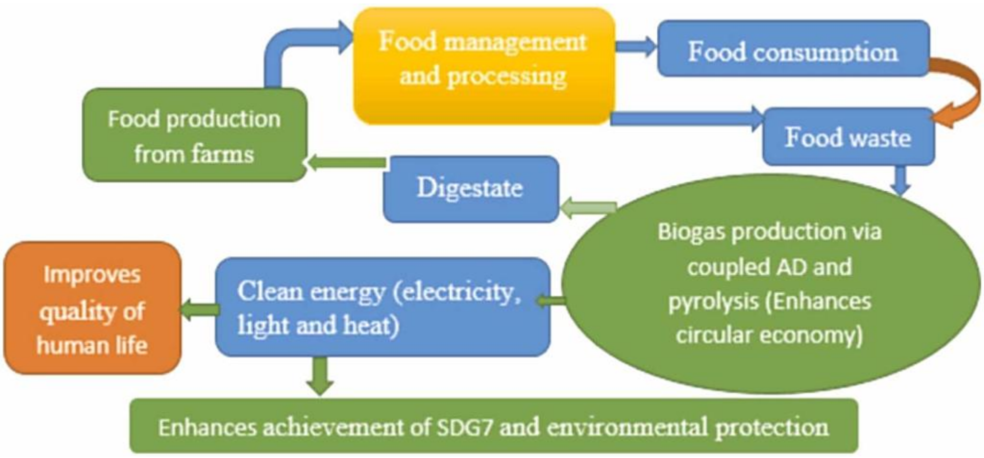

Fig. 1. A graphical illustration emphasizing the relationship between food production and waste and the circular economy (Emmanuel et al., 2024)

sustainable development goal is to “ensure access to affordable, reliable, sustainable and modern energy for all”. Specifically, SDG 7.3a aims to “facilitate access to clean energy research and technology” by 2030 (United Nations, 2015). The development of biogas technology will make positive contributions to the attainment of SDG 7 since it enables cleaner generation and consumption of energy compared to fossil fuels. According to (Obaideen et al., 2022), the development and use of biogas offers an opportunity for decentralized and democratized energy generation as rural communities can generate their energy from waste generated by their activities (which includes agricultural activities) without depending on electricity and gas grids. However, they noted a downside to the use of biogas due to the generation of methane which is a greenhouse gas. The discharge of methane accidentally or through other means in the production and handling of biogas will have to be checked and properly managed to ensure sustainability in the production and use of biogas.

3. 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 (Amani et al., 2010). 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 (Gulnar Gadirli et al., 2024). Anaerobic Digestion involves four phases where different groups of microorganisms work in coordination to bring about digestion (Gulnar Gadirli et al., 2024). They are outlined below:

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 (Akhilesh Kumar Singh et al., 2023; Xue et al., 2020). These bacteria include Bacteroides, Sporobacterium, Propionibacterium, Sphingomonas, Megasphaera, Lactobacillus, and Bifidobacterium. They secrete large, stable and complex enzymes for use in the Hydrolysis reaction (Keerthana Devi et al., 2022). These enzymes include Cellulase, Xylanase, and Protease (Keerthana Devi et al., 2022). The Hydrolysis phase is often preceded by a pre-treatment stage which removes the barriers hindering microbial digestion, making the substrate’s organic content to be accessed and utilized more easily by the bacteria (Patinvoh et al., 2017). The hydrolysis phase of the AD process may be shortened by employing a pre-treatment step which would depend on the structure and characteristics of the biomass being used (Kasinath et al., 2021). The process of hydrolysis is represented by the equation below (Uddin & Wright, 2022).

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2 \qquad (1)$$

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 (Chandra et al., 2012; Xue et al., 2020). The products of this phase can be influenced by factors such as pH (Ivanchenko et al., 2021). Some bacteria involved in this phase include Micrococcus, Streptococcus, Peptococcus, Escherichia coli, and Desulfomonas working under aerobic and anaerobic conditions. They secrete enzymes such as acetate kinase, C-acetyltransferase, acetaldehyde, hydrogen lyase, and dehydrogenase (Keerthana Devi et al., 2022). The process of acidogenesis is represented by the equations below (Uddin & Wright, 2022).

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \qquad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \qquad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \qquad (4)$$

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 (Gkamarazi, 2015; Pilarska et al., 2018; Uddin & Wright, 2022). Also called the dehydrogenation stage, this phase involves the conversion of fermented products into small molecules in a reaction during which the production of acetic acid is high (Lü et al., 2021). This phase is represented by the equations below (Uddin & Wright, 2022).

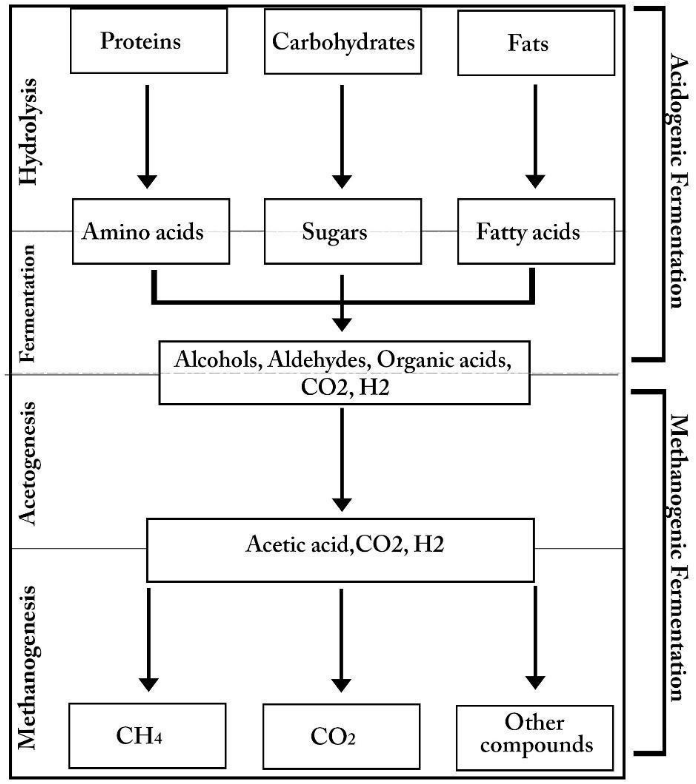

Fig. 2. A schematic of the Anaerobic Digestion process. Adapted from (Gulnar Gadirli et al., 2024)

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO3^- + 3H_2 \quad (5)$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (6)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H \quad (7)$$

The Methanogenesis phase: In the methanogenesis phase, methanogens are employed to convert hydrogen and CO_2 into methane. This they achieve by the reduction of CO_2 and oxidation of Hydrogen. Acetolactic methanogens also produce methane from acetate (Kalyuzhnyi et al., 2000). Methanogenesis produces about 70% of the methane in an Anaerobic Digestion process, thus playing an important role (Pilarska et al., 2019). Fig. 2 gives a summary of the Anaerobic Digestion process. The methanogenesis process is represented by the set of equations given below (Uddin & Wright, 2022).

4. BIOGAS PLANTS TECHNOLOGY

Biogas plants thrive on the Anaerobic Digestion process to obtain renewable energy from organic waste in the form of biogas (Gulnar Gadirli et al., 2024). According to (Pilarska et al., 2019; Spuhler, 2014) a biogas digester is a sealed, air-tight 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 (Chodkowska-Miszczuk & Szymańska, 2013; Prakash et al., 2005). Agricultural biogas plants are suited for agricultural feedstock (Gulnar Gadirli et al., 2024). 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 (Xue et al., 2020).

(Mutungwazi et al., 2018) in their work on digesters classified biogas digester types based on operational mode into passive systems, low-rate systems, and high-rate systems and based on scale into domestic or residential digesters and small and commercial medium-scale digesters. The design of biogas plants involves analyzing the substrates, the demands of the production, and the operating conditions for production (Arnold, 2011; Gulnar Gadirli et al., 2024). Concisely, the principle of biogas plants involves the entry of feedstock either directly or after a mixing stage, the retention of the substrate, the collection of biogas, and then its exit through an outlet for use (Bond & Templeton, 2011).

4.1 Types of Biogas Designs

(Mutungwazi et al., 2018) 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:

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 (Rajendran et al., 2012). 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 (Mutungwazi et al., 2018). To ensure smooth flow through the reactor, the solid content in the feed needs to be high about the range <10–15%. The plug flow digester is illustrated in Fig. 3.

The lagoon digester: A lagoon is a two-cell waste treatment and storage system (Hamilton, 2014). 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 odours even in cold areas, and function best with liquid manures that contain less than 2% total solids (Mutungwazi et al., 2018). The lagoon digester is illustrated in Fig. 4.

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 (Mutungwazi et al., 2018). The complete mix digester is illustrated by the schematic diagram in Fig. 5.

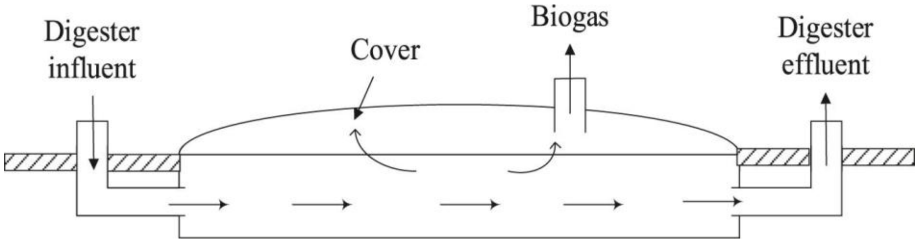

Fig. 3. A schematic diagram of a plug flow digester (Uddin & Wright, 2022)

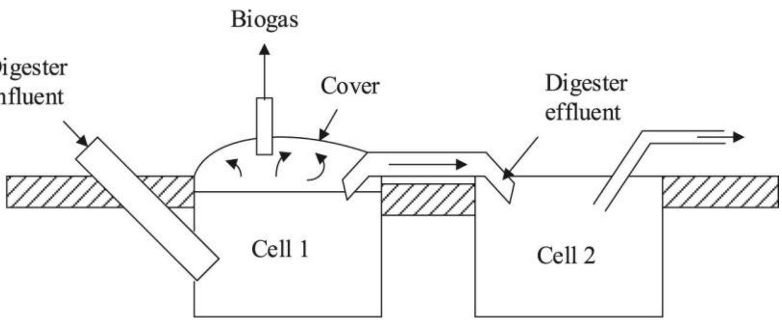

Fig. 4. A schematic diagram of a closed lagoon digester (Uddin & Wright, 2022).

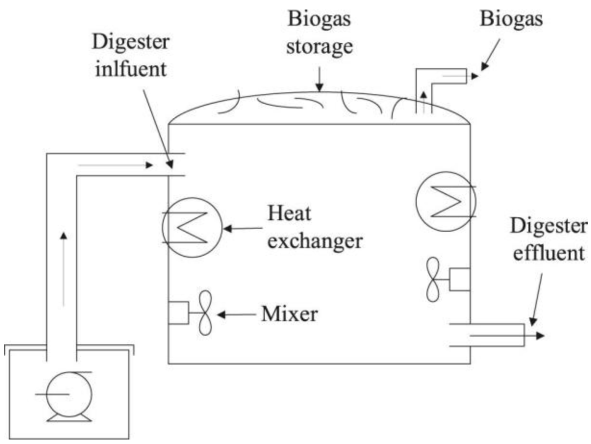

Fig. 5. A schematic diagram of a complete mix digester (Uddin & Wright, 2022).

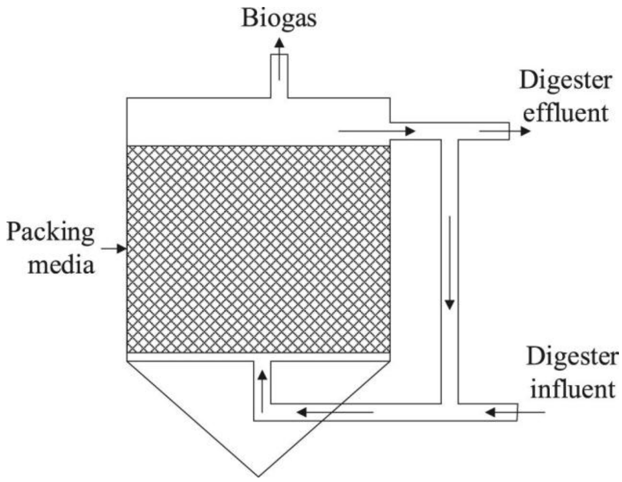

Fig. 6. A schematic diagram of a fixed film digester (Uddin & Wright, 2022)

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 (Mutungwazi et al., 2018). Because of the narrow flow space associated with this digester design, it is not suitable for all substrate types. Also, it is applicable for feedstock with solid content of 1-2% as higher solid content can cause clogging of the flow through the film. Lastly, it is characterized by a short hydraulic retention time (HRT) of 2-6 days (Uddin & Wright, 2022). The fixed film digester is illustrated by the diagram in Fig. 6.

5. FACTORS AFFECTING BIOGAS PRODUCTION THROUGH ANAEROBIC DIGESTION

Several factors play roles in enhancing or reducing biogas production through Anaerobic Digestion. Temperature regulates the rate of microbial metabolism (Rahman et al., 2021). Various findings show a direct relationship between temperature and the volume of biogas produced (Dhungana et al., 2022). According to (Wang et al., 2019), low temperatures proved unfavorable for the acidogenic and methanogenic stages of biogas production and moderate temperatures (typically above 25°C) proved favorable for methanogenesis. Also, (Vanegas & Bartlett, 2012) conducted a study on anaerobic digestion using seaweed and noted that the highest volume of biogas was generated by the mesophilic (30°C) reactor while the biogas produced by the thermophilic (45°C) reactor had a methane content which was lower by 23.3% and that by the psychrophilic (20°C) reactor by 39.7%. The pH of the system, by influencing the microbial communities, also affects the rate of biogas production. (Dai et al., 2016) while studying the pH effect on biogas production from sewage sludge and cattle manure noted that the volatile acid production and the methane yield reduced with pH values above or below 9.0. The bacteria group dominated at the pH of 9.0 making it the optimum pH condition. (Xu et al., 2021) also noted that the pH of the anaerobic digestion process, by altering the community of microbes, influenced sCOD accumulation, reduced the volatile fatty acids and total solids content and, overall, improved methane yield by 16.6%. The Total Solids (TS) refers to all solids suspended or dissolved in the digestion medium (Onwosi et al., 2022). The TS concentration influences the community of microbes, the TS reduction rate, and as a result, the methane yield from the system (Patil et al., 2012). (Emmanuel et al., 2024) in a review on anaerobic digestion using food waste noted that the optimal concentration of total solids in AD using food waste ranges between 8% and 30%. However, this factor varies with the nature of the food waste and the co-substrate. The moisture content also affects biogas production through anaerobic digestion. According to recent reports, the moisture content influences biogas generation from food waste within 70% - 97% of moisture, depending on the substrate used. In an AD process using rice husks, the biogas yields at 90%, 80%, and 70% moisture were 1.13, 1.25, and 1.03 m^3 respectively, with the highest yield at 80% (Sathish et al., 2017). Another study showed that including biochar in the anaerobic digestion of food waste improved the biogas yield. A moisture content of 90% improved the daily methane production by 136% (Indren et al., 2020). The hydraulic retention time (HRT) also plays a crucial role in methane yield through AD (Onwosi et al., 2022). Reducing the HRT often demands process optimization and may require pre-treatment and other adjustments to system conditions which will alter the microbial community positively (Landi et al., 2013).

6. BIOGAS DIGESTATE MANAGEMENT: A TRENDING GLOBAL CHALLENGE TO SUSTAINABLE BIOGAS PRODUCTION

In establishing biogas production as a tool for sustainable development, it is necessary to ensure that all stages of the value chain are sustainable. In recent times, much interest has grown in the sustainable management of biogas digestate (Malhotra et al., 2022). According to (Malhotra et al., 2022), digestate management and disposal have become a challenge for AD operators, rising with the increase in the size of digester plants. While biogas production provides a sustainable source of energy, the digestate formed from this process can cause environmental problems when not properly managed. Associated with the unscientific, excess, and indiscriminate disposal of digestate are issues such as water pollution as a result of excess nutrients, accumulation of heavy metals, accumulation of recalcitrant organics, and pathogen contamination (Koszel & Lorencowicz, 2015; Malhotra et al., 2022; Parmar & Ross, 2019; Walsh et al., 2012). In Europe, excess disposal of digestate has led to surplus nutrients in many regions which can lead to serious pollution and emission of greenhouse gases (BMU & BMEL, 2020; Rizzioli et al., 2023). Other concerns have been raised such as the presence of harmful compounds in biogas digestate which includes pesticides, hormones, pharmaceuticals, phenols, personal care products, persistent organic compounds, and microplastics (Christina van Midden et al., 2023). Therefore, there is a need to develop effective means and technologies for the sustainable management and disposal of biogas digestate. In the management of biogas digestate, several treatment and processing methods have been developed. Their goal is to make the digestate more fit and safer for applications and to valorize it into other useful products. The processing method employed depends on the physicochemical properties of the digestate. This also determines its final use (Lamolinara et al., 2022). The methods could either be biological (bioremediation), chemical (e.g. oxidation (Stanisław Wacławek et al., 2016)), or physical (e.g. screening, settling, or floatation) (Lamolinara et al., 2022). For example, in liquid-solid separation, a promising method for converting digestate into a nutrient-rich fluid with valuable products and also free of pollutants is the use of membrane filtration (Zacharof & Lovitt, 2014). The membrane filtration through liquid-solid separation enables the aqueous phase to be used as a medium for growing algae, microbes, and plants. This phase is usually enriched with dissolved organic nutrients. The solid phase which has fewer nutrients can then be employed as a soil amendment (Silkina et al., 2017). Depending on the particle sizes, diverse membrane technologies can be employed in digestate processing such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis) (Gerardo et al., 2015; Zacharof et al., 2015, 2016). Table 1 gives a summary of relevant and promising technologies for processing biogas digestate.

Table 1. Biogas digestate processing technologies (Lamolinara et al., 2022)

Method	Main characteristics	Application	Considerations	Scale	References
Membrane filtration (microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and forward osmosis)	Involves a simple physical process which does not require adding chemicals. Particle separation is based on size. The costs of operation and maintenance are lower compared to other separation methods.	Used to remove small particles such as microorganisms, suspended solids, small organic molecules macromolecules, and ions from liquid fractions. The permeates can be used as green fertilizers being rich in N and K.	Scaling the high power and maintenance requirement. Occurrences of membrane-blocking	Full-scale and lab-scale	(Céline Vaneeckhaute et al., 2011; Guo et al., 2012; Masse et al., 2007)
Thickening (filtration, gravity settling, air flotation, and centrifugation)	The digestate is concentrated up to the extent of 5-10% suspended solids	Used to separate liquid and solid fractions of the digestate	Other treatment methods need to be applied to ensure efficient recovery of nutrients	Full scale	(Monfet et al., 2017)
Thermal drying	The solid fraction can be pelletized after drying to enable better management. It is usually valorised through thermochemical means or used as a source of animal litter.	Employs the forced convection of hot air to expel water from dewatered solid fractions	High consumption of energy	Full scale	(Pedrazzi et al., 2015)
Ammonia stripping	After stripping, the recovered ammonia can be converted into an ammonia salt which can find application in chemical or agricultural industries.	Employs air or steam stripping to remove ammonia from the liquid fraction. This process can be applied directly to digesters to save costs on ammonia recovery.	Increasing the pH from 10.8 to 11.5 is required. High energy consumption leads to increased costs.	Full scale	(Raboni et al., 2015; Serna-Maza et al., 2014)
Dewatering	The water in the solid fraction is removed to yield a solid concentration of 15-35%.	The concentration of suspended solids in the solid fraction through the removal of water	Complimentary treatment methods are required for more efficient nutrient recovery.	Full scale	(Chernicharo, 2006)
Biomass production and harvest	Dilution is often required. Light penetration is reduced	Employs biological technology to recover nutrients in the liquid fraction (84–98 % N, and 90–99 % P)	Requires large surface area. It is often toxic if the Nitrogen concentration exceeds 60mg/l	Full, pilot, and lab scale	(Vaneeckhaute et al., 2016)

7. AGRICULTURAL WASTE AVAILABILITY AND POTENTIAL FOR BIOGAS PRODUCTION IN NIGERIA

7.1 Nigeria's Agricultural Waste Supply

Agriculture has played an important role in Nigeria and several other African countries for the sustenance of citizens and the economy through the cultivation of food crops and cash crops (Austin, 2009; Ireti Olamide, 2015). Nigeria's crop production ranges from different crop types and in abundant quantities to meet the demands. Fig. 7 gives the production data for select crops in Nigeria for the year 2022 according to the FAOSTAT report (FAO, 2023). This rate of crop production is often accompanied by waste production from crops. Indeed, agricultural waste production is not only limited to crop farming but also includes waste produced from the rearing of livestock. (Odejobi et al., 2022) outlined biomass feedstock sources in Nigeria, accounting for agricultural waste such as animal manure from cattle, pig, sheep, poultry, and dogs, and crop residues such as straw, stalk, bark, cobs, and husk. (Ibiwumi Damaris Kolawole et al., 2024) further classified agricultural residues into primary agricultural residues and secondary agricultural residues, both from crops and also accounted for agricultural waste obtained from livestock.

Nigeria generates a large amount of agricultural waste yearly. This production has been accounted for by various researches conducted at different periods. (Ngumah et al., 2013) in 2013 employed mathematical computation to estimate that Nigeria produces 542.5 million tonnes of selected organic waste annually. (Akinbomi et al., 2014) estimated that an average of 172 million tonnes of residues were obtained from crops through harvesting and processing operations. This evaluation covered a broad range of crops cultivated in Nigeria. In another study, (Oyegoke et al., 2023) conducted an analysis, estimating the annual agro-waste generation from a few select crops that are commonly cultivated in Nigeria. They adopted data from the FAOSTAT and NBS databases and also made use of the crop-to-waste mass ratio and overall waste fraction, captured in other reviews as the residue-to-product ratio (RPR). This ratio is of great importance in analyzing the generation of waste or residues from crops. The residue-to-product ratio is an index, indicating the weight of residue obtained from a particular crop based on the amount of the crop produced (Iye & Bilsborrow, 2013). It varies from crop to crop as they possess structural differences. The findings of (Oyegoke et al., 2023) are represented in Table 2. They estimated that 12.06 Mt of agro-waste is generated annually in Nigeria. This value was limited to crop production and did not take into account waste generated from livestock. It also shows a significant disparity with the reports of (Akinbomi et al., 2014). This can be accounted for by the smaller range of crops considered in this case and the difference in sources cited for the RPR index. Nevertheless, a common observation seen in both reports is the huge potential of agricultural waste available for biogas production. Nigeria produces lots of waste from agricultural activities that can be valorized through anaerobic digestion into biogas to meet some of the energy demands on farms, especially in rural communities.

These crop residues show geographical variations in their availability. According to (Okoro et al., 2024), the various geopolitical zones in Nigeria demonstrate diversified agroecological conditions, allowing for the cultivation of a broad range of crops and diverse systems of agriculture. The soil conditions, farming practices, and climate in the respective zones also influence the crop type, area cultivated, and yields for various crops. The crop residue distribution for major residue-producing crops is illustrated in Fig. 8 There is significant biomass potential for cowpeas, yam, rice, and sorghum in the northwest, northeast, and north-central regions. The high moisture content of yam and sorghum residues makes them ideal for biochemical processes like AD. Also, the South-South region has significant biomass potential for rice, yam, cassava, and oil palm. Because of their high moisture content, yam and cassava residues are ideal for biochemical processes like fermentation and AD (Okoro et al., 2024).

7.2 The Biogas Potential of Agricultural Waste Generated in Nigeria

Having evaluated the supply of agricultural waste in Nigeria for biogas generation, the next step will be to evaluate the potential of various waste types generated for biogas production. (Ezealigo et al., 2021) outlined an analytical procedure presented below.

Crop residues: In estimating the biogas potential of crop residues and livestock waste, (Ezealigo et al., 2021) outlined an analytical procedure which is presented below:

Table 2. Agro-waste production from selected crops in Nigeria. Adapted from (Oyegoke et al., 2023)

Crops	Potential waste	Crop to waste mass ratio (CW)	Waste fraction (overall) $\sum \frac{1}{CW}$	AnnuaL crop production (Averaged) Mt	Waste produced (Mt)
Cassava	Stem, peel	Peel = 100/17 Stem = 9/1	0.0671	50.80	3.41
Maize	Cob, straw, stalk	Straw = 9/1 Cob = 6/5 Stalk = 7/4	0.0837	9.28	0.78
Sorghum	Straw, bagasse, stalk	Stalk = 7/3 Bagasse = 6/4 Straw = 9/1	0.0779	7.10	0.55
Groundnut	Stem, shell, leaves	Hull = 0.89/0.30 Stem = 8/2	0.1435	3.61	0.52
Millet	Stalk, leaves	Leaves = 6/4 Stalks = 4/6	0.4615	2.42	1.12
Cowpea	Stem, shell, leaves	Shell = 6/4 Stem = 6/5 Leaves = 9/1	0.08547	3.23	0.28
Sugarcane	Leaves, bagasse	Bagasse = 9/3 Leaves = 9/1	0.0833	1.32	0.11
Potato	Leaves, peel	Peel = 9/3 Leaves = 9/1	0.0833	1.07	0.09
Yam	Leaves, peel, stem	Peel = 91/9 Leaves = 95/5 Stem = 95/5	0.0208	40.42	0.84
Palm Oil Fruit	Leaves, empty fruit bunch, kernel shell	Kernel shell = 4/6 Leaves = 9/1 Empty Fruit Bunch = 4/6	0.0968	8.58	0.83
Rice	Straw, husk	Straw = 3/5 Husk = 9.7/1.9	0.1753	5.65	0.99
Sweet Potato	Leaves, peel	Peel = 8/2 Leaves = 9/1	0.0769	3.56	0.27
Tomato	Stem, leaves	Leaves = 6/4 Stem = 5/5	0.4000	2.65	1.06
Plantain	Peels	Peels = 8/3	0.3750	2.91	1.09
Pineapple	Stem, peel, leaves	Stem = 9/3 Peel = 9/1 Leaves = 9/1	0.0476	1.31	0.06
Mango	Seed, peel	Peel = 9/1 Seed = 9/3	0.0833	0.84	0.07
Total	**-**	**-**	**2.3615**	**144.75**	**12.07**

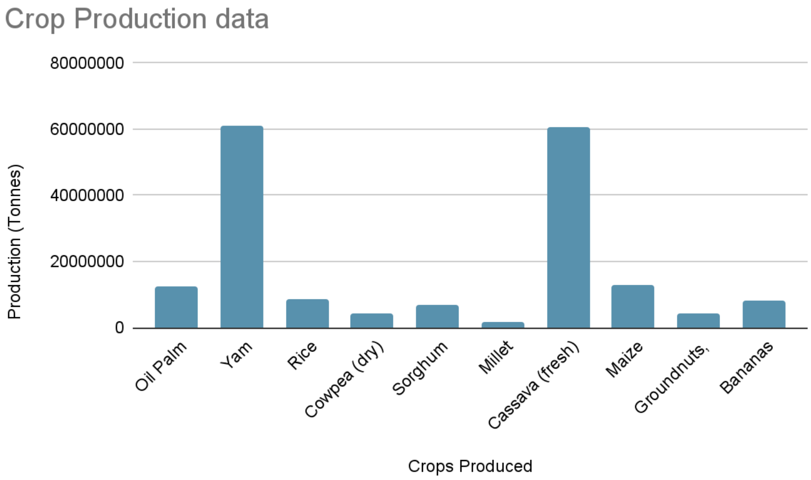

Fig. 7. Production data for select crops in Nigeria for the year 2022 (FAO, 2023)

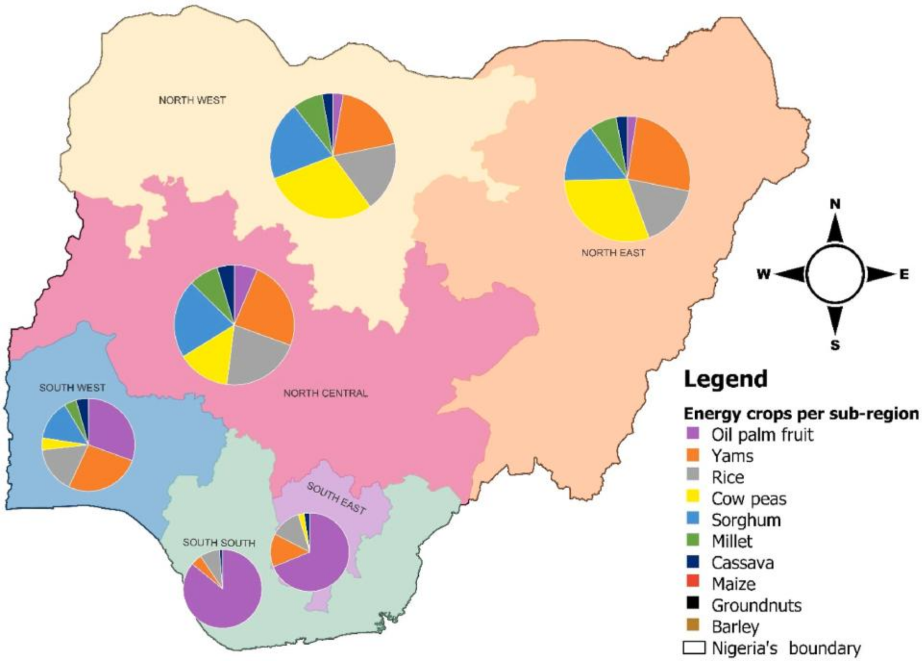

Fig. 8. Crop residue distribution in Nigeria (Okoro et al., 2024)

(a). Theoretical crop residue potential (P_{th}): This is the product of the total specific crop available for a given year and the residue-to-product ratio for the crop

$$P_{th} = P_{crop} \times RPR \quad (8)$$

However, they noted that because crop residues can be utilized for other purposes, the use of the theoretical residue potential was not realistic as these other residue utilization forms may pose competition with the available residue for biogas generation. In a similar vein, (Akinbomi et al., 2014) reported that approximately 70% of crop residues from harvesting and processing are utilized for animal fodders and materials for construction. According to their analysis, crop residues provide 58% of animal fodder, especially during the rainy season. Thus, it was estimated that 52 million tonnes of crop residues remained for the production of biogas after the rest had been used for other purposes, from which 21 billion cubic meters of biogas may be generated.

(b). Technical crop residue potential (P_{tech}): Therefore (Ezealigo et al., 2021) considered the portion of the crop residue that is recoverable for biogas production, referring to it as the technical crop residue potential. It is given as:

$$P_{tech} = P_{th} \times R_f \quad (9)$$

P_{tech} = Technical potential, Rf = Recoverable fraction

(c). Biogas potential: (Ezealigo et al., 2021) estimated the biogas potential by first determining the Buswell biomethane potential (BMP)

$$\gamma_{BMP\ Buswell} = (\gamma_{Buswell,glu} \times C_{glu}) + (\gamma_{Buswell,hem} \times C_{hem}) \quad (10)$$

Where:

$\gamma_{BMP\ Buswell}$ = the estimated biodegradable fraction for biogas production in specific crop residue as obtained from the Buswell formula.
$\gamma_{Buswell,glu}$ = the estimated glucan in specific residue as obtained from the Buswell formula.
$\gamma_{Buswell,hem}$ = the estimated hemicellulose as obtained from the Buswell formula.
C_{glu} = The glucan concentration
C_{hem} = The hemicellulose concentration

Livestock residues: The technical potential was obtained similarly to that of crop residues.

$$\gamma_{man}(theoretical\ potential) = P_{livestock} \times EMP \quad (11)$$

$$\gamma_{man}(technical\ potential) = \gamma_{man}(theoretical\ potential) \times R_f \quad (12)$$

γ_{man} = manure produced
EMP = Estimated manure produced per day

The biogas potential was obtained by the equation below with the value of the biomethane potential (V_{BMP}) as 0.26111 m³ CH_4/kgVS

$$LMM = \gamma_{man}(technical\ potential) \times C_{TS} \times VS \times \gamma_{BMP} \quad (13)$$

LMM = Livestock Manure Methane
VS = Volume Solid
C_{TS} = Total Solid Concentration

(Ngumah et al., 2013) in 2013 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%. They also reported the biogas potential from different biomass in Nigeria as represented in Fig. 9.

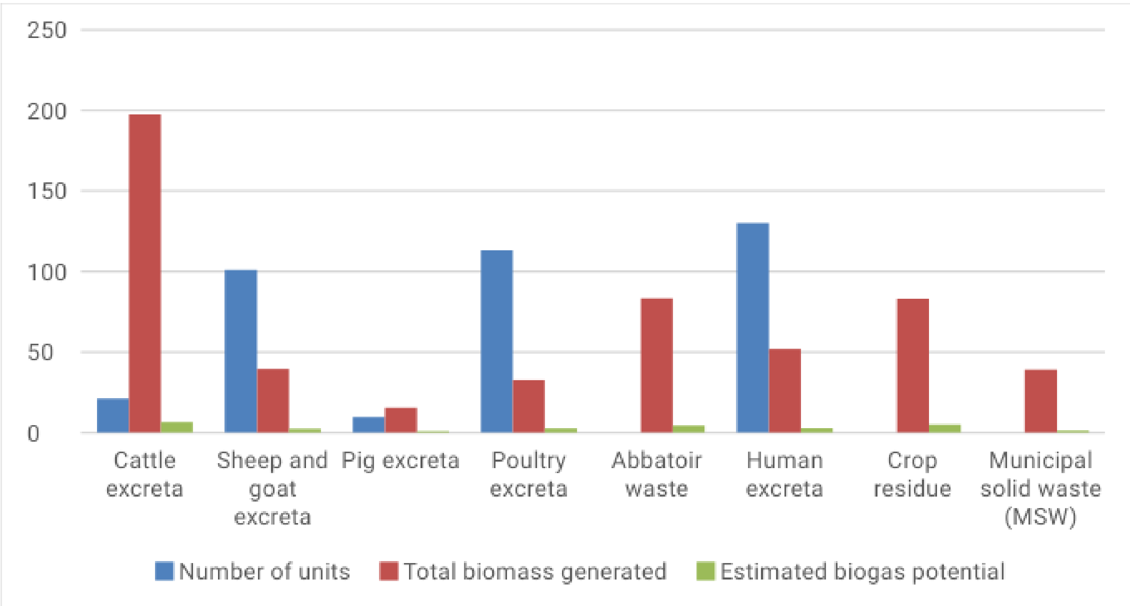

Fig. 9. Different biomass generated in Nigeria shows the potential of biogas derivable (Ngumah et al., 2013)

Table 3. Biogas potential from crop residues from 2008-2018 (Ezealigo et al., 2021)

Year	Theoretical (Mt)	Technical (Mt)	Mm^3 CH4/yr	Mtoe
2008	115.82	90.53	15,859.26	13.69
2009	90.45	71.10	12,405.56	10.71
2010	106.94	84.18	14,534.41	12.55
2011	93.88	72.37	13,198.36	11.39
2012	103.69	81.06	14,024.91	12.11
2013	97.14	75.60	13,095.00	11.31
2014	112.97	86.81	15,747.22	13.59
2015	115.95	89.13	16,173.43	13.96
2016	125.79	97.20	17,571.09	15.17
2017	116.14	88.66	16,144.15	13.94
2018	118.54	90.84	16,404.53	13.94
Average	108.85	84.32	15,014.36	12.96

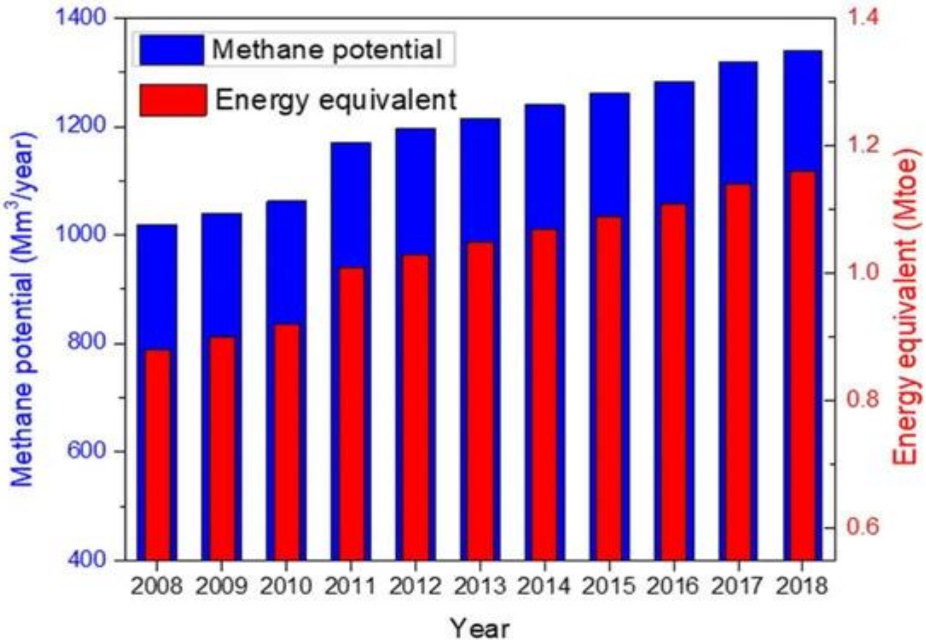

Fig. 10. Energy potential from livestock waste in Nigeria (Ezealigo et al., 2021).

Table 4. Biogas yield from livestock manure in Nigeria (Jekayinfa et al., 2020)

Animal	Unit ($\times 10^6$)	Daily dung generation (Kg)	Biogas Yield (m^3 /kg Dry Matter)
Camels	0.282	20	0.14–0.19
Pigs	7.506	1–4.5	0.37–0.56
Chickens	140.688	0.05–0.15	0.28–0.40
Sheep	42.5	1–5	0.25–0.37
Horses	0.103	13–15	0.24–0.37
Rabbits and hares	0.005	0.01-0.06	0.10–0.21
Goats	78.037	1–5	0.25–0.37
Asses	1.313	10	0.24

Okonkwo et al., (2018) stated that 227500 tonnes of fresh animal waste were produced in Nigeria daily of which 1kg had a biogas production capacity of $0.03m^3$. He further stated that Nigeria had a 6.8 million m^3 biogas production potential from the waste produced. (Ezealigo et al., 2021) performed their analysis using the method earlier described, for crop residues between 2008 and 2018, estimating the theoretical and technical residue potentials as well as the biogas potential for each year. They are represented in Table 3. They inferred from the average values of the theoretical and technical residues (109 and 84 Mt respectively) that the technical residues can sustain biogas production in Nigeria. Furthermore, they represented data for the estimate of the biogas potential from livestock manure during the same period, pointing out an increasing trend in the biogas produced over that period. They also noted a linear trend in the methane potential and energy equivalent as shown in Fig. 10. Table 4 also shows the biogas potential for selected animal waste in Nigeria. Generally, (Ezealigo et al., 2021) reported that an average of 84Mt of technical residue potential is obtained from 143Mt of crops produced, thus availing only about 58% for energy production. They also noted a linear relationship between crop production and biofuel production. An interesting part of their findings was that biogas had the highest energy potential among other biofuels evaluated, with 15014 Mm^3 on average from crop residues.

(Odejobi et al., 2022) by reviewing various scientific databases between 1997 and 2020 examined the agricultural, industrial, and municipal waste in Nigeria and their biogas production potential. They cited animal manure, energy crops, and crop residues as potential agricultural biogas sources. The study by (Odejobi et al., 2022) concluded that an estimated 227500 tonnes/day of animal manure generated biogas of 6.8 million m^3/day while 83 million tonnes/year of crop residues generated 4.98 billion m^3/year of biogas. He also reported the estimated annual energy potential for crop residues at 3635.95 PJ/yr and that for animal manure at 450.48 PJ/day.

Energy generation from biomass through processes such as anaerobic digestion is promising in Nigeria. The Federal Ministry of Environment in a collaborative action with the United Nations Development Program (UNDP) accounted for biomass resources in the Renewable Energy Master Plan (REMP) (Ayamolowo et al., 2019). The REMP, launched in 2006, seeks to enhance renewable energy integration into Nigeria's energy mix (Davidson Chukwudi Onwumelu, 2023). Table 5 gives the targeted energy generation from renewable sources as captured by the REMP.

8. RECENT 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 (Odejobi et al., 2022). In Nigeria, biogas production has advanced significantly due to the nation's initiatives towards sustainable energy generation and waste management (Nwoke et al., 2023; Subbarao et al., 2023). There are several biogas plants in Nigeria, varying in scale and capacity and positioned in areas with significant waste production (Amoo et al., 2023; Nwoke et al., 2023). Small-scale biogas plants are used in rural areas to meet the energy demands and waste management needs (Adebare Johnson Adeleke et al., 2023). In their research on the current situation of anaerobic digestion for biogas production in Nigeria, (Adebare Johnson Adeleke et al., 2023) 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-litre 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:

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

Table 5. Renewable Energy Master Plan (REMP) renewable energy generation targets (Akorede et al., 2016; Ayamolowo et al., 2019)

Energy Source	2010 (MW)	2015 (MW)	2030 (MW)
Large hydro	1,930	5,930	48,000
Solar PV	5	120	500
Small hydro	100	734	19000
Solar Thermal	0	1	5
Wind	1	20	40
Biomass	0	100	800
Total RE	2,036	6,905	68,345
Total Energy Resources	16,000	30,000	192,000
RE Percentage (%)	13	23	36

These are just a few among several projects that exist. Unfortunately, it is worth noting that Nigeria has not successfully implemented biogas production on a large scale. (Ngumah et al., 2013) 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. (Okonkwo et al., 2018) 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. (Adebare Johnson Adeleke et al., 2023) 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, (Eze I.S et al., 2011) 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 farming communities. In a report by (Villages, 2016), 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.

9. 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:

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 (Odejobi et al., 2022). According to (Oyedepo et al., 2019), 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 (Odejobi et al., 2022). (Nwankwo et al., 2024) identified policy as the major limiting factor to biogas technology penetration in Nigeria among other developing countries. According to them, biogas technology, which might offer a dependable energy mix and also serve as an agent for the nation to meet its climate goals, has not received the necessary attention. This is because there is no clear framework for the strategic development, deployment, and use of biomass technology in Nigeria's energy policy. Examples of approved policies in the Nigerian energy sector include the National Energy Policy (2003, 2006, and 2013), National Electric Power Policy (2002) Roadmap for Power Sector Reforms (2010), Rural Electrification Policy Paper (2009), National Determined Contribution (2015), and National Renewable Energy and Energy Efficiency Policy (2015) (Power, 2016).

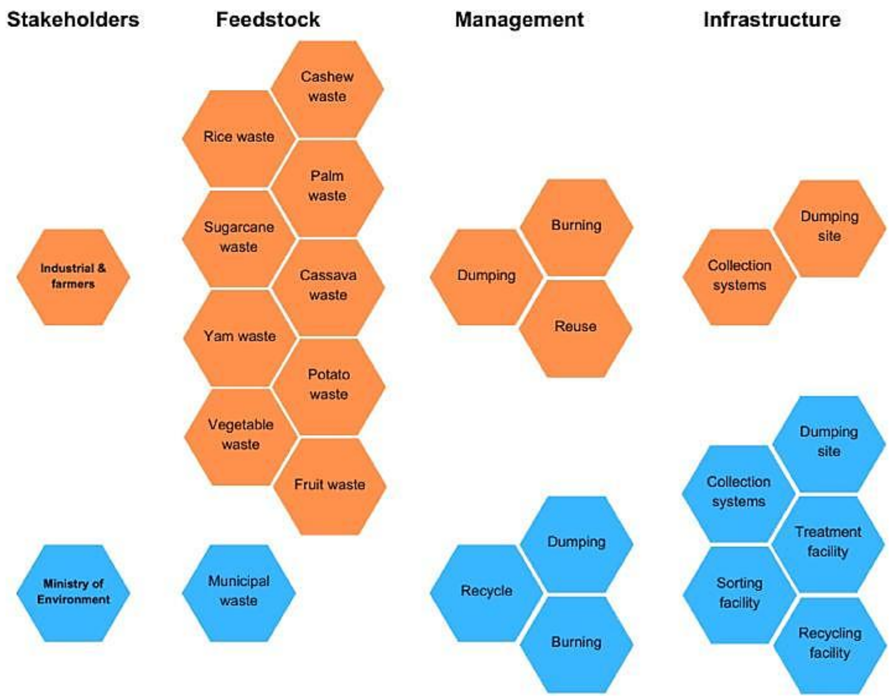

Fig. 11. Waste management practices among various stakeholders (Okoro et al., 2024)

Lack of sufficient funding: The cost of biogas plant acquisition is huge in terms of operation and maintenance (Kemausuor et al., 2018). The income obtainable from subsistence farming, which is largely practiced among rural farmers, is not sufficient for them to acquire biogas plants (Odejobi et al., 2022). This challenge is prohibitive to the implementation of biogas technologies. (Audu et al., 2020) in a review highlighted some challenges to the implementation of AD technology for abattoir waste. These included policies being more favourable towards fossil-based energy seen through the high lending rates and availability of public subsidies. They linked the problem of funding to policies and highlighted a need to address the issues through political means and public policies.

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 (Odejobi et al., 2022). 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 (Kemausuor et al., 2018). (Okoro et al., 2024) investigated the potential of agri-residues in Nigeria using a biomass mapping approach and also identified existing knowledge gaps in the utilization of agri-residues. The outcome of the biomass mapping conducted revealed that there is a significant amount of disaggregated agri-residue in Nigeria and many knowledge gaps in the use of biomass as a sustainable source of energy to be integrated into Nigeria's energy mix. They confirmed their findings by holding interviews with stakeholders from relevant sectors who were not aware enough of other modern bioenergy applications. Fig. 11 summarizes their findings, representing the current waste management practices among the stakeholders.

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 (Odejobi et al., 2022). (Emmanuel et al., 2024) in a review on the use of food waste for biogas generation in Sub-Saharan Africa identified a challenge to the implementation of biogas technology in the short supply of feedstock resulting from the SDG 12.3 target of reducing food waste to zero. Therefore, other means might be put in place to utilize food waste or to even reduce and prevent its generation. This applies to other waste streams used in anaerobic digestion. According to them, a challenge to the use of food waste is the competition in its use for biogas generation with its use as a source of animal feed. This is supported by the concepts of theoretical and technical residue potentials earlier explained in which (Akinbomi et al., 2014) reported that of crop residues from harvesting and processing activities, approximately 70% are utilized for animal fodders and construction materials. The competition in use will create a short supply of biomass feedstock for AD.

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 (Kemausuor et al., 2018). 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 (Adebare Johnson Adeleke et al., 2023).

10. COUNTERMEASURES FOR OVERCOMING THE CHALLENGES

Public awareness creation: The lack of awareness poses a major limitation to the development of biogas technologies. Communication media such as newspapers, Televisions, and radios, among others, need to be employed in the dissemination of information concerning biogas technologies to rural farmers. There is also a need for enlightenment on developments in biogas technologies. These moves should be coupled with efforts to provide cost-effective digesters to local farmers. Generally, governmental and non-governmental organizations have roles to play in these respects (Ajibola & Junior, 2013; Bond & Templeton, 2011; Rajendran et al., 2012; Surendra et al., 2014; Walekhwa et al., 2009). 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 (Vasco-Correa et al., 2018). 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 (Davidson Chukwudi Onwumelu, 2023).

Policy development and implementation: The advancement of AD technology is closely linked to policies, regulations, and incentives 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 (Vasco-Correa et al., 2018). 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 (Davidson Chukwudi Onwumelu, 2023). Table 6 outlines several stakeholders who are relevant towards the implementation of biogas production in Nigeria. According to (Nwankwo et al., 2024), the nation should secure, develop, and integrate technologies that would harness biomass resources effectively, integrating them with other sources of energy; foster the use of anaerobic digestion; ensure efficient management of waste by promoting landfill value chain operations; promote the use of biogas technologies to capture residues and waste at the farm gate.

Table 6. Agencies and stakeholders relevant towards biogas legislation in Nigeria. Adopted from (Babajide Epe Shari et al., 2023)

S/N	AGENCY	STAKEHOLDERS/PARTNERS
1	International agencies	GIZ Nigeria United Nations Development Programme (UNDP)
2	National agencies	Rural Electrification Agency Energy Commission of Nigeria (ECN) Nigeria Energy Support Programme (NESP)
3	Government agencies	Federal Ministry of Power Federal Ministry of Agriculture and Food Security Federal Ministry of Science, Technology and Innovation
4	Funding agencies	Africa Development Bank (AfDB) Commercial Banks
5	Research institutes	National Center for Energy Research and Development
6	Non-Governmental agencies	Leadership for Environment and Development (LEAD) Nigeria Heinrich Boll Foundation Nigeria

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. Start-ups aiming to enter the clean energy industry can receive support from private institutions such as commercial banks, venture capitalists, and private equity financing organizations (Davidson Chukwudi Onwumelu, 2023). (Audu et al., 2020) identified solutions to the challenges hindering the uptake of abattoir wastes in Nigeria and they include public policies in support of investments in the private sector. This support can come through national programs aimed at providing research and development, marketing, technical, aiding access to funding from climate change incentives, providing funding and financial support, as well as regulating framework guiding participation and involvement of the private sector.

Research and development: According to (Jekayinfa et al., 2020), there is a need for more research into characterizing more biomass sources for bioenergy production. Some biomass types and sources are yet to be explored. Further study is necessary to explore the usability of yet-to-be-explored biomass sources which include agricultural waste streams. They also noted that developing the agricultural sector will lead to a growth in bioenergy production in Nigeria through the generation of more biomass resources and because fostering the agricultural sector will yield lesser competition between alternative biomass utilization and bioenergy. They also encouraged community-based power generation for rural electrification using residues from rural agricultural activities.

11. FUTURE PROSPECTS

The current trend of Biogas utilization 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 (Akinbomi et al., 2014) 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 (Scarlat et al., 2018). 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 favorable policies are implemented and the infrastructure also made available. Biogas can contribute significantly to 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 (Scarlat et al., 2018). These are 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 a means of improving the biological digestion process (Scarlat et al., 2018). This is expected to be accompanied by 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 policies are implemented, favouring the production and utilization of biogas in Nigeria, especially in its rural agricultural sector.

12. CONCLUSION

The rise in various environmental challenges on our planet such as ocean acidification, global warming, air pollution, etc, has led to the need to design processes that meet the needs of society without compromising the quality of life on the planet. As conventional means of energy production exist as a major contributor to climate change, biofuel production provides a cleaner pathway for energy generation today. This review sought to assess the potential of biogas production as a sustainable energy source in rural agricultural communities in Nigeria. The process and technology of biogas production were reviewed in which digestate management, a trending challenge to the sustainability of biogas production, was discussed. Technologies for the effective management of biogas digestate were also highlighted including membrane separation, thickening, ammonia stripping, dewatering, thermal drying, etc. The crop production potential, the crop residue potential, and livestock residue production in Nigeria were also assessed, demonstrating Nigeria to be a producer of a large amount of agro-waste, with up to 84Mt in the technical potential of crop residues annually and up to 227500 tonnes of fresh animal waste generated daily. This has the potential of generating up to 6.8 million m^3/day of biogas from animal manure and 15.014 billion m^3/year from crop residues. These results demonstrate an untapped potential in the agricultural waste generated in Nigeria to supply biogas for energy demands on farms. Recent trends in the implementation of biogas technologies showed that Nigeria has not been successful in implementing biogas technologies, especially on a large scale, with most of the progress limited to research and small-scale plants. Several challenges were identified, revealing the absence of effective policies and regulatory frameworks as the major challenge hindering the implementation of biogas production, alongside the lack of public awareness, technical expertise, etc. By overcoming these challenges, Nigeria will be able to make significant progress in biogas implementation and this will foster biogas uptake in rural areas. The successful implementation of biogas production in rural areas will not only aid in clean energy generation but also promote sustainable development through the creation of jobs and reduction of environmental pollution.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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