UJMR, Vol. 8 No. 2, December, 2023, pp. 153 - 164

E-ISSN: 2814 – 1822; P-ISSN: 2616 – 0668

https://doi.org/10.47430/ujmr.2382.018

Received: 05 October 2023 **Accepted:** 24 December 2023

Anaerobic Digestion Technology for Biogas Production: Current Situation in Nigeria (A Review)

Adeleke, A.J[1*]., Ajunwa, O.M[2]., Golden, J.A[1]., Antia, U.E[3]., Adesulu-Dahunsi, A.T[4]., Adewara, O.A[5]., Popoola, O.D[6]., Oni, E.O[7]. Thomas, B.T[6]., Luka Y[8].

[1]Department of Microbiology, Modibbo Adama University, Yola, Nigeria
[2]Interdisciplinary Nanoscience Center, Aarhus University, Aarhus, Denmark
[3]Department of Microbiology, Akwa Ibom State University, Ikot Akpaden, Akwa Ibom State
[4]Department of Biological Sciences, Thomas Adewumi University, Oko, Kwara State, Nigeria
[5]Department of Biological Science and Biotechnology, Caleb University, Lagos, Nigeria
[6]Department of Microbiology, Olabisi Onabanjo University, Ago-Iwoye, Nigeria
[7]Department of Microbiology, Federal University of Agriculture, Abeokuta, Nigeria
[8]Department of Chemical Engineering, Modibbo Adama University, Yola, Nigeria
*Corresponding author: lekejohnson2222@mau.edu.ng

Abstract

In view of the nation's vast agricultural resources, crop residues, animal manure, municipal waste, and wastewater sludge may be transformed into renewable energy, potentially a source of revenue. Biogas production offers cleaner, sustainable solutions across the nation. The compass of supportive policy and regulation emerges, guiding investment toward transformative shores. Various "Waste-to-Energy" academic researches and pilot projects illuminate paths to energy generation, waste management and sustainability with the prospects of a viable bioeconomy. The application of anaerobic digestion technology contributes to a greener and more sustainable energy future. In Nigeria, biogas production holds multifaceted benefits which include energy sustainability waste management, and climate change mitigation. By harnessing organic waste, energy source diversification reduces reliance on fossil fuels. Biogas mitigates environmental pollution, converts waste to value, which is key to climate goals. Sustaining biogas production requires incentives, research, expertise, public awareness, and infrastructure. Collaboration and strategic partnerships will likely accelerate Nigeria's biogas production potential. In conclusion, this review underscores the immense potential of biogas production in Nigeria. It seeks to enliven the discussion for fostering efficient management of the abundant organic resources, supportive policies, public engagement, technological advancements, and partnerships that can bring about a wider implementation of biogas production projects across Nigeria towards a greener and sustainable energy future.

***Keywords:** Anaerobic digestion, biogas, methane, organic wastes, Nigeria*

INTRODUCTION

Anaerobic digestion technology is a biotechnological process which leverages the capability of microorganisms to convert organic matter into a valuable energy resource, biogas (Kim *et al.,* 2010; Ampese *et al.,* 2022). Functioning in the absence of oxygen, it conditions an anaerobic environment where a myriad of microorganisms collaborate harmoniously to breakdown complex organic compounds into simpler substances, primarily methane (CH_4) and carbon dioxide (CO_2) (Kim *et al.,* 2010; Rasapoor *et al.,* 2020; Thompson *et al.,* 2020). This biologically driven process exhibits immense potential as a sustainable and eco-friendly solution for waste management and renewable energy production (Kumar and Samadder, 2020; Uddin *et al.,* 2021). The natural occurrence of anaerobic digestion is observed in diverse environments, including wetlands and landfills, where organic matter decomposes in the absence of oxygen. Scientists and engineers have made significant progress over the years, refining and optimizing this natural process, culminating in engineered systems that produce biogas on a larger scale (Wainaina *et al.,* 2020; Diamantis *et al.,* 2021). These engineered anaerobic digesters are designed to maintain the ideal conditions for microbial activity, there by maximizing biogas yields and overall efficiency.

During the anaerobic digestion process, microbial communities collaborate symbiotically to execute different stages of organic matter degradation (Diamantis *et al.,* 2021).

In the initial phase, hydrolytic bacteria adeptly breakdown complex organic compounds into simpler molecules such as fatty acids, amino acids, and reducing sugars (Khanal *et al.,* 2021; Iglesias *et al.,* 2021). Subsequently, acidogenic bacteria convert these simpler compounds into volatile fatty acids and alcohols. Finally, methanogenic archaea function in the vital step of transforming these intermediates into methane and carbon dioxide through a process known as methanogenesis (Anukam *et al.,* 2019; Bijarchiyan *et al.,* 2020). Notably, ongoing research continues to unveil novel insights into the intricacies of anaerobic digestion, enabling scientists and engineers to fine-tune the process further, leading to enhanced biogas production and even broader applications. By harnessing the collective intelligence of microbial communities and merging it with cutting-edge engineering principles, anaerobic digestion holds the potential to revolutionize waste management and usher in a new era of sustainable energy production, mitigating environmental impacts and propelling us towards a greener future (Kumar and Samadder, 2020; Uddin *et al.,* 2021). As technology evolves, it is evident that the alliance between science and nature can pave the way for a more sustainable and harmonious coexistence with our planet.

The historical origins of biogas production can be traced back to ancient civilizations in Assyria in the 10th century BC and Persia in 16th century AD, where indigenous communities utilized animal dung and other organic wastes for energy purposes (Bijarchiyan *et al.,* 2020). These early applications marked the initial instances of harnessing biogas as a renewable energy source. However, it was not until the mid-19th century that biogas gained more substantial attention as a viable technology for energy production (Kim *et al.,* 2010). A notable milestone in the history of biogas technology was the construction of the first modern anaerobic digester in India during the late 1800s (Ahammad and Sreekrishnan, 2016). This ground-breaking digester effectively harnessed biogas for practical applications, including street lighting and cooking, thereby demonstrating the vast potential of this renewable energy source for daily use (Maciel-Silva *et al.,* 2019; Vyas *et al.,* 2022; Kor-Bicakci and Eskicioglu, 2019). Since then, biogas production has undergone continuous evolution and global expansion, firmly establishing itself as a prominent player in the realm of renewable energy.

In recent years, the importance of biogas technology has grown exponentially, fuelled by increasing concerns about environmental sustainability and the imperative to shift towards cleaner energy sources (Anukam *et al.,* 2019; Bijarchiyan *et al.,* 2020). One of the most compelling advantages of biogas production lies in its capacity to mitigate the release of methane, a potent greenhouse gas, into the atmosphere while simultaneously providing a reliable energy supply that complements conventional fossil fuels. Additionally, the utilization of organic waste as feedstock for biogas production not only addresses waste management challenges but also fosters the concept of a circular economy. As the world marches steadily towards a greener and more sustainable future, biogas production emerges as a vital and indispensable component of the renewable energy mix (Pramanik *et al.,* 2019; O'Connor *et al.,* 2021). With relentless advancements in technology and a deeper understanding of microbial processes, anaerobic digestion continues to hold tremendous potential in meeting the escalating global energy demands while ardently championing environmental conservation and sustainable development (Li *et al.,* 2023; Singh *et al.,* 2023; Maria *et al.,* 2023). The journey of biogas, from its origins in ancient civilizations to its current status as a cornerstone of renewable energy solutions, exemplifies the ingenuity of human innovation and our quest for a more sustainable and eco-friendlier world. As researchers and engineers continue to explore new frontiers in anaerobic digestion technology, it is the hope that biogas plays a more essential role in shaping a cleaner, greener, and more harmonious planet for generations to come.

SIGNIFICANCE OF BIOGAS PRODUCTION IN NIGERIA

Nigeria, a developing nation and one of the most populous countries in Africa, grapples with enormous challenges in meeting its surging energy demands (Ekwenna*et al.,* 2023). Presently, the energy sector in Nigeria is predominantly reliant on fossil fuels, with oil and gas dominating the energy supply landscape. However, this heavy dependence on fossil fuels has engendered a host of issues, including energy insecurity, environmental degradation, and alarming greenhouse gas emissions (Babatola *et al.,* 2023; Riagbayire and Nayem, 2023). Against the backdrop of Nigeria's escalating energy needs and the imperative to transition towards more sustainable energy sources, biogas production has emerged as a pivotal and transformative player. As a renewable and clean energy resource, biogas offers a plethora of benefits for Nigeria's energy mix. Foremost, biogas production strategically taps into the abundant organic waste streams available in the country, such as agricultural residues, food waste, and livestock manure).

By adequately converting these organic materials into biogas, Nigeria can address pressing waste management challenges while simultaneously producing much-needed energy (Babatola *et al.,* 2023). Beyond waste management benefits, biogas can serve as an indispensable decentralized energy solution, particularly in rural areas where access to centralized power grids remains limited. Local biogas production facilities have the potential to empower communities by providing reliable electricity and cooking gas, thereby elevating livelihoods and improving overall energy access (Dickson *et al.,* 2023; Ore *et al.,* 2023). Moreover, biogas production serves as a potent ally in the fight against greenhouse gas emissions. The anaerobic digestion process employed in biogas production captures methane, effectively preventing its release into the atmosphere. This mitigation action can contribute significantly to Nigeria's climate commitments and foster sustainable development goals (Dickson *et al.,* 2023; Ore *et al.,* 2023). The integration of biogas into Nigeria's energy mix, by tapping into its rich organic waste resources and embracing decentralized biogas facilities, heralds a promising era of cleaner and more sustainable energy solutions that will serve as a catalyst for progress and prosperity for the nation and its people.

ANAEROBIC DIGESTION PROCESS AND TECHNOLOGY

Anaerobic digestion process explained

At the heart of anaerobic digestion lies a fascinating interplay of diverse microorganisms, each playing a crucial role in the process of converting organic matter into biogas and digestate (Bhatt and Tai, 2020; Messineo *et al.,* 2020). Microorganisms collaborate in a series of reactions orchestrating a symphony of biochemical transformations. Understanding the pivotal role they play is essential for maximizing biogas production efficiency and unlocking the full potential of this sustainable process (Yang *et al.,* 2023; Yue *et al.,* 2023). Bharathiraja *et al.,* (2018) presented potential feedstock sources appropriate for anaerobic digestion, including energy crops, agricultural waste, municipal biowaste, industrial waste and waste water. The first stage, hydrolysis, sets the foundation for the entire process, as hydrolytic bacteria take center stage. These microorganisms breakdown complex organic materials such as proteins, fats, and carbohydrates, into simpler compounds, including amino acids, fatty acids, and sugars (Maciel-Silva *et al.,* 2019; Messineo *et al.,* 2020). Subsequently, acidogenesis unfolds, orchestrated by acidogenic bacteria, where the simpler compounds from hydrolysis are further metabolized into volatile fatty acids such as acetic acid, propionic acid, and butyric acid (Maciel-Silva *et al.,* 2019; Li *et al.,* 2023). The stage of acetogenesis follows, guided by acetogenic bacteria, which transform the volatile fatty acids into acetic acid, hydrogen, and carbon dioxide, preparing the substrates for the final stage of methanogenesis (Kor-Bicakci and Eskicioglu, 2019). Finally, the methanogenic archaea complete the process of biogas production. In the methanogenesis stage, these microorganisms convert the products from acetogenesis into biogas, predominantly composed of methane (CH_4) and carbon dioxide (CO_2) (Kor-Bicakci and Eskicioglu, 2019; Vyas *et al.,* 2022). This intricate balance and succession of microorganisms orchestrates the transformation of organic matter into biogas, unveiling the potential of anaerobic digestion as a sustainable and eco-friendly energy solution.

Factors affecting efficiency of biogas production during anaerobic digestion

A number of factors are important to consider while determining the efficiency of biogas production. The whole process of conversion involves a microbial succession mechanism that has to be sustained in a delicate manner for consistency in the product yield and quality. Some of these factors are explained below:

A. Feedstock Composition: The composition of organic material used as feedstock is a pivotal determinant of biogas yield (Kim *et al.,* 2010). Substrates rich in easily degradable compounds, such as carbohydrates and lipids, provide a more favorable environment for microbial activity, resulting in higher biogas production rates. Conversely, feedstock with a high lignin content or complex molecular structures may require longer digestion times and may yield lower biogas volumes due to the increased microbial effort and time needed for breakdown.
B. Temperature: Anaerobic digestion is highly temperature dependent, with different groups of microorganisms thriving within specific temperature ranges (Maria *et al.,* 2023; Singh *et al.,* 2023). Maintaining the optimal temperature in the digester is critical for enhancing microbial activity and maximizing biogas production. Psychrophilic microorganisms operate at lower temperatures, while mesophilic and thermophilic bacteria are more active at moderate to higher temperatures. Understanding and controlling the temperature is essential for achieving efficient biogas production and preventing process inhibition.

C. pH Level: Regulating the pH level within the anaerobic digester is fundamental to maintaining microbial activity and ensuring optimal performance (Maria *et al.,* 2023; Yang *et al.,* 2023). Anaerobic digestion typically operates within a neutral to slightly acidic pH range. Deviations from this range can disrupt the microbial ecosystem, leading to process instability and reduced biogas yields. Monitoring and adjusting the pH as needed is essential for sustained biogas production.

D. Retention time: The duration that the substrate spends in the digester, known as retention time, plays a crucial role in the overall efficiency (Zhao *et al.,* 2021). Longer retention times offer microorganisms extended opportunities to breakdown complex substrates, particularly lignocellulosic materials, resulting in higher biogas yields. The choice of retention time should be carefully optimized based on the specific feedstock and microbial community present in the digester.

E. Mixing and agitation: Adequate mixing and agitation within the digester are essential to ensure the uniform distribution of microorganisms and nutrients throughout the substrate (Maciel-Silva *et al.,* 2019; Vyas *et al.,* 2022; Otieno *et al.,* 2023). Proper mixing prevents the formation of localized zones with varying conditions, promoting efficient digestion and preventing the accumulation of solids that can impede gas production. Effective mixing also helps maintain stable operating conditions and prevents stratification within the digester.

F. Inhibitory substances: The presence of inhibitory substances, such as heavy metals and chemicals, can severely hinder microbial activity and reduce the efficiency of biogas production. These substances can act as toxicants, negatively impacting the microbial community responsible for anaerobic digestion. Proper pretreatment or removal of inhibitory substances is essential to maintain the health and functionality of the microbial consortium and ensure consistent biogas generation.

Types of anaerobic digesters

Anaerobic digesters are versatile systems used for converting organic materials into biogas, but they come in different types to suit various needs (Kim *et al.,* 2010; Li *et al.,* 2023; Singh *et al.,* 2023). First, batch systems are characterized by their discontinuous operation. In these digesters, a fixed quantity of organic material is loaded, and the digestion process continues until completion (Obileke *et al.,* 2021; Kunatsa and Xia, 2022). Batch systems are simple and cost-effective, making them suitable for smaller-scale applications and research purposes. However, their intermittent operation can lead to fluctuations in biogas production.

Fed-batch systems, a variation of batch digesters, offer more control and capacity. Here, organic material is intermittently added during the digestion process, allowing for semi-continuous operation (Kor-Bicakci and Eskicioglu, 2019; Zhao *et al.,* 2021). This approach enhances efficiency and enables the digestion of larger volumes of waste. Fed-batch systems are often preferred in agricultural settings, where waste materials are generated intermittently, and in medium-scale applications. They strike a balance between the simplicity of batch systems and the continuous operation of other types (Masebinu *et al.,* 2019; Obileke *et al.,* 2021).

Continuous systems, in contrast, operate without interruption. They receive and digest organic materials continuously, providing a steady supply of biogas. Continuous digesters are more complex in design but are highly efficient and versatile (Kunatsa and Xia, 2022; Kumar *et al.,* 2021). They are suitable for larger-scale applications, such as municipal wastewater treatment plants, industrial facilities, and large agricultural operations. Continuous systems, including plug flow digesters, ensure a consistent biogas output and are essential for scenarios where a continuous supply of renewable energy is crucial. In comparing digesters based on efficiency, applicability, and cost-effectiveness, the choice of digester type hinges on various factors, such as the scale of the biogas project, available feedstock, energy demand, and budget. Probable comparison:

Efficiency: Continuous digesters and plug flow digesters generally boost higher biogas production rates due to their consistent feeding and optimal flow patterns. Complete mix digesters can also be efficient if appropriately designed and managed (Ampese *et al.,* 2022; Kumar and Samadder, 2020).

Applicability: Continuous digesters prove ideal for large-scale biogas plants with a stable feedstock supply, while batch digesters offer more flexibility and are suitable for smaller facilities or scenarios with varying feedstock types (Vyas *et al.,* 2022; Kor-Bicakci and Eskicioglu, 2019).

Cost-effectiveness: Batch digesters often present lower capital costs since they possess simpler designs and can be constructed with less complexity. On the other hand, continuous digesters, despite being more expensive to build, may yield better long-term returns due to their higher biogas production rates (Masebinu *et al.*, 2019; Obileke *et al.*, 2021).

By carefully considering the unique attributes of each digester type, stakeholders in biogas projects can make informed decisions that align with their specific needs and goals. Whether aiming for large-scale energy production or seeking flexible solutions for smaller setups, the diverse array of anaerobic digesters provides a wealth of possibilities for harnessing the potential of biogas as a sustainable and renewable energy resource.

Current advancements in anaerobic digestion technology

Over the years, significant progress has been made in anaerobic digestion technology to improve biogas yields, shorten retention times, and increase the biodegradability of various feedstocks (Singh *et al.*, 2023; Maria *et al.*, 2023; Yang *et al.*, 2023; Yue *et al.*, 2023; Otieno *et al.*, 2023). One notable advancement is the development of high-rate anaerobic digesters, such as upflow anaerobic sludge blanket (UASB) reactors and expanded granular sludge bed (EGSB) reactors. These technologies allow for faster biogas production and are particularly useful when dealing with high-strength organic waste streams (Vyas *et al.*, 2022; Kor-Bicakci and Eskicioglu, 2019). Moreover, innovative approaches, such as two-stage and multistage anaerobic digestion, have been explored to optimize the degradation of complex organic compounds, resulting in increased biogas production and improved digestion efficiency (Messineo *et al.*, 2020; Maciel-Silva *et al.*, 2019; Li *et al.*, 2023; Singh *et al.*, 2023; Maria *et al.*, 2023; Yang *et al.*, 2023)

BIOGAS PRODUCTION IN NIGERIA: CURRENT STATUS AND CHALLENGES

Overview of biogas projects in Nigeria

The drive towards sustainable energy generation and waste management in Nigeria has spurred significant progress in the field of biogas production, presenting a promising and transformative solution to address critical environmental and energy challenges (Nwoke *et al.*, 2023; Subbarao *et al.*, 2023). As Nigeria takes firm strides towards a greener and more sustainable future, biogas emerges as a compelling tool, harnessing the potential of organic waste to generate renewable energy and minimize environmental impacts (Subbarao *et al.*, 2023; Nwoke *et al.*, 2023). Nigeria hosts a number of biogas plants of varying scales at strategic locations. These facilities exhibit diverse capacities and are often positioned in regions with significant organic waste generation (Nwoke *et al.*, 2023; Amoo *et al.*, 2023). In rural areas, smaller-scale biogas plants predominantly prevail (with no formal documentation), catering to the local energy needs and waste management demands. These decentralized systems utilize resources such as animal manure, crop residues, and kitchen waste as feedstock (Ajaero *et al.*, 2023; Zanna and Jatto, 2023). The resulting biogas finds common applications in cooking, lighting, and sometimes electricity generation. Conversely, urban centres and industrial hubs have potentials for larger-scale biogas plants designed to handle municipal solid waste, agro-industrial residues, and wastewater sludge.

A biogas plant was launched in Ikorodu Mini Abattoir, at Ebute road, Ikorodu, Lagos State in 2019. The plant was capable of converting organic waste through the installation of four 5,000-litre digester tanks, and fed with digestible organic waste and concentrated wastewater from the abattoir. Biogas generated was used to power the abattoir for close to six hours daily according to the report on the Guardian Newspaper (GN 2019). The project was carried out by Lagos State government, Friends of the Environment (FOTE) and HIS Biogas. Also, a renewable energy company based in Lagos (Avenam) as reported on the company website (https://avenamlinks.com/gallery/) has in conjunction with other stakeholders set up a number of biogas plants at various locations in Nigeria. These include: (i) a portable biogas plant project executed in collaboration with University of Benin and Lancaster University to generate electricity to a portion of the school's administrative building through co-digestion of food waste and cow dung. (ii) Anaerobic Baffled Reactor for sewage management with biogas production at a correctional facility in Lagos. Gas generated was used as cooking gas (iii) Biogas Plant for electricity generation through gas produced from co-digestion of cassava peels and cow dung at a factory in Ibadan, Oyo State. (iv) Biogas Sewage Treatment Plant at a student hostel in Calabar to generate gas for cooking. (v) Biogas Plant built in Ogun State to convert poultry waste to electricity and organic fertilizer. (vi) Biogas Plant built in a community in Bayelsa State to generate electricity for the community. Toilets were built for the community, so that the waste from toilets could be used as feedstock for the biogas plant.

(vii) A $10m^3$ biogas system built in Lagos, Nigeria to produce biogas form cow dung treatment for cooking. However, the biogas production capacity and the current operational status of these biogas plants could not be ascertained for the purpose of this review. In the year 2022, International Institute of Tropical Agriculture (IITA), Ibadan launched an anaerobic digestion biogas plant which was to provide the general IITA Staff Canteen and Cappa Canteen with energy supply for cooking using various biodegradable wastes available in the IITA premises. A waste separation system was earlier installed in 2019 which was to aid the availability and utilization of biodegradable wastes amidst the mixtures of wastes materials (IITA, 2022) Other examples include the biogas plant constructed in Zaria Prison, Kaduna State, Mayflower School Ikene, Ogun State and one of the plants built in Usman Danfodiyo University, Sokoto State, in Northern Nigeria (Akinbomi *et al.*, 2014).

There are also a number of researches on biogas production in Nigeria. Ikpe *et al.* (2019) reported the possibility of producing biogas from different food wastes and that certain food wastes like gari (with purified biogas of 120g) has higher biogas yield than others (which include sweet potatoes, corn, rice, beans etc.) based on their study on conversion of these food wastes to biogas. However, it is opined that promoting these kinds of wastes from edible food substances may lead to food security risk as certain entrepreneurs may end up embarking on the use of the food items for biogas production. In this case, there may be competition between the use of certain food items as raw materials for biogas production and as food for human and animal consumption. Therefore, focus should be on bioconversion of agricultural wastes derived from the crops of these food items for biogas production. Hassan *et al.* (2023) studied the use of animal wastes mixed with empty bunches of oil palm fruits (EBPF) to generate biogas for cooking. Their results showed that it is best to combine cow dung with EBPF in a ratio not exceeding minimal use of EBPF at acidic and moderate temperature. The highest average percentage by volume of methane (74%) was obtained when cow dung was mixed with EBPF at ratio 4 to 1. As biogas from anaerobic digester is piped through a filter, then into an orifice and fired in a burner, Ozigis *et al.* (2019) explained that many of the pilot biogas digesters built by various agencies in Nigeria were not working due to poor quality of construction and that the periodic lack of gas supply to burner and lamp can be attributed to mismatch of biogas digester systems and lack of design to predict gas generation and slurry discharge. They then designed an anaerobic biogas plant that matched a given cooker and gas lamp sets by carrying out the sizing of the component parts of a dome type anaerobic biogas digester plant, prediction of slurry flow rate into exit chamber, and performance evaluation of biogas burner and mantle lamp. It was observed among other things that biogas generation showed a trend that could be described by exponential polynomial. Ekwenna *et al.* (2023) investigated the use of a three-stage anaerobic digestion system for the co-production of hydrogen and methane gases from rice straw. Stage one involved hydrogen production from rice straw hydrolysates after pretreatment. Stage 2 involved methane production from organic acids which resulted from stage 1 while stage 3 was the methane production from dried rice straw residues after pretreatment. It was reported that hydrogen yield from rice straw improved with Sodium hydroxide and potash extract pretreatment having maximum yields of 114 NmL H_2 g^{-1} TS d^{-1}) and PE-PT (103 NmL H_2g^{-1} 1 TS d^{-1}) respectively while methane production efficiency was also reported to be 80% and 75% respectively. However, there is no record of an industrial application of this three-stage approach in the country as at the time this review was written.

Challenges and limitations of biogas technology in Nigeria

Despite the promising prospects, implementation of biogas production in Nigeria is not without challenges and limitations (Yusuf *et al.*, 2023; Aworanti *et al.*, 2023). In fact, there is no large-scale production of biogas in Nigeria at the moment. Most existing anaerobic digestion plants are owned by agricultural processing firms and household individuals. Many promising laboratory scale researches by Nigerian scholars have not been upgraded and the few pilot biogas plants have been marred with discontinuity due to several factors which include the technical hurdles in effectively digesting the diverse range of organic feedstocks and the socioeconomic barriers impeding the widespread adoption of biogas technology.

Technical challenges in digesting diverse organic feedstocks

The efficiency of biogas production heavily relies on the composition and characteristics of the organic feedstocks utilized. Nigeria's vibrant agro-industrial activities result in a cornucopia of feedstocks, each exhibiting different degradation rates and biogas yields. This poses technical challenges in designing biogas plants that can optimally digest this diverse array of organic waste (Anyaoha and Zhang, 2023; Yusuf *et al.*, 2023).

Certain organic materials, such as lignocellulosic residues, may prove recalcitrant to anaerobic digestion, leading to prolonged retention times and diminished biogas output. Technical research and development play a pivotal role in honing the digestion of such intricate substrates, exploring pretreatment techniques that enhance biodegradability, and adapting digester configurations to accommodate various feedstock complexities.

Socioeconomic barriers hindering widespread adoption

The wide-scale acceptance of biogas technology in Nigeria confronts socioeconomic barriers that necessitate resolution to foster the sector's growth and long-term sustainability. These formidable barriers encompass the following:

a) *Initial Investment Costs:* Establishing biogas plants, particularly larger-scale systems, demands substantial upfront investments. Many potential investors may perceive these capital costs as prohibitive, particularly in the absence of clear financial incentives or access to favorable financing options.

b) *Lack of Awareness and Technical Expertise*: Limited awareness about biogas technology and its manifold benefits can hinder its widespread adoption. Additionally, the dearth of skilled technical personnel proficient in designing, operating, and maintaining biogas plants could serve as a deterrent to potential stakeholders.

c) *Infrastructure and Access to Markets:* In remote areas, where the potential for biogas production is considerable, inadequate infrastructure, such as grid connectivity and waste collection systems, might curtail the feasibility of biogas projects.

d) *Policy and Regulatory Support*: Ambiguous or inconsistent policies and regulations concerning biogas production and renewable energy could sow seeds of uncertainty among investors and developers, hindering long-term commitments to this eco-friendly technology.

(e) Inadequate waste sorting from the source: One of the primary challenges is the lack of proper waste sorting at the source. Without effective waste segregation practices at households and businesses, organic waste that could be valuable for biogas production is often mixed with nonbiodegradable waste. This hinders the efficiency of biogas plants, as the presence of certain toxic substances can disrupt the anaerobic digestion process and reduce biogas yields.

(f) Incorrect Disposal Practices: Incorrect disposal practices, such as open dumping and burning of waste, are prevalent in many parts of Nigeria. These practices not only lead to environmental pollution but also result in the loss of organic waste that could be utilized for biogas production. This challenge underscores the need for widespread awareness campaigns to promote responsible waste disposal.

(g) *Limited access to high-quality feedstock:* The quality of feedstock is crucial for efficient biogas production. In Nigeria, access to a consistent supply of high-quality organic waste can be a limitation. Inconsistent waste collection and a lack of proper waste sorting mean that biogas plants often receive mixed and contaminated feedstock, which can reduce biogas production rates and quality.

(h) *Financial barriers*: Establishing biogas plants, particularly larger-scale systems, involves substantial upfront investment costs. Many potential investors may find these capital requirements prohibitive, especially in the absence of financial incentives or accessible financing options.

PROSPECTS AND CIRCUMVENTIONS FOR BIOGAS TECHNOLOGY IN NIGERIA

Potential feedstock sources for biogas production

Biogas technology holds immense promise in shaping Nigeria's sustainable energy future, providing a reliable and renewable energy source while effectively mitigating the environmental impacts of organic waste (Aworanti *et al.*, 2023; Ekwenna *et al.*, 2023). As one of Africa's most populous nations, Nigeria generates a substantial volume of organic waste from diverse sources, including agricultural residues, municipal solid waste, animal manure, food processing by-products, and wastewater sludge. The selection of feedstock should carefully consider factors such as availability, local context, and the chosen technology for anaerobic digestion. For instance, agricultural residues such as crop stalks, fruit peels, and husks hold tremendous promise as excellent feedstock, particularly in rural areas rich in agricultural activities (Ajaero *et al.*, 2023; Ofomatah *et al.*, 2023; Zanna and Jatto, 2023). In urban centres, municipal solid waste and food waste represent effective feedstock options for biogas production. Furthermore, the vast reservoir of livestock manure from poultry, cattle, and other livestock farming can serve as a valuable input for biogas plants, especially in regions with a high concentration of animal husbandry. This abundance presents a treasure trove of opportunities for biogas production. However, the efficient harnessing of these feedstocks requires overcoming challenges such as inadequate waste management practices, the absence of proper collection and segregation systems (Figure 1 shows example of municipal waste in Nigeria which often lacks proper sorting), and limited awareness of biogas technology's advantages (Riagbayire and Nayem, 2023; Yusuf *et al.,* 2023). To unlock the full potential of biogas adoption, concerted efforts are needed to enhance waste management infrastructure and foster robust public–private partnerships to establish efficient waste collection systems. The strategic utilization of diverse feedstock ensures a steady supply of raw materials for biogas plants.

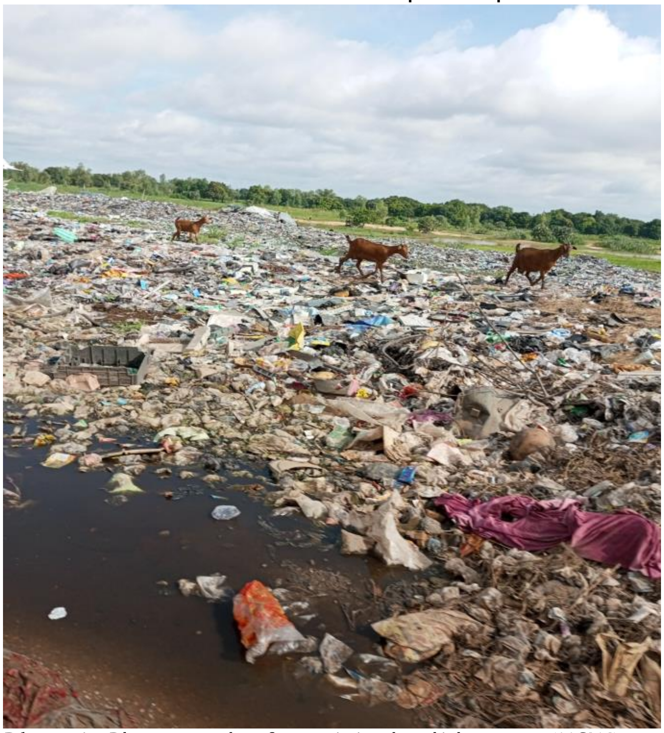

Plate 1: Photograph of municipal solid waste (MSW) makeshift landfills in Jimeta, Yola.

Circumventions and considerations:

A. Bioaugmentation: To enhance biogas production, bioaugmentation, the introduction of specific microorganisms, can be employed to speed up the rate of anaerobic digestion of waste materials. However, its successful application depends on selecting and maintaining the appropriate microbial community for the specific feedstock. Proper monitoring and control of microbial populations are essential to prevent imbalance and ensure consistent biogas production.

B. Biostimulation: Biostimulation involves manipulating the physicochemical conditions to stimulate the existing microbial communities for improved biogas yields during anaerobic digestion. Understanding feedstock compatibility is crucial for biostimulation. Different organic materials have varying carbon-to-nitrogen ratios, which can affect the efficiency of the microbial community. Hence, proper feedstock management and adjustments can be achieved by adding appropriate nutrients.

C. Policy framework: The development of a robust policy framework that supports biogas technology is vital. This includes clear regulations, incentives, and financing options to encourage investment in biogas projects. Consistent and supportive policies can address some of the financial barriers associated with biogas projects implementation. The government should consider introducing or enhancing feed-in tariffs and other financial incentives to make biogas projects economically viable and attractive to investors (Anyaoha and Zhang, 2023; Aworanti *et al.,* 2023; Ekwenna *et al.,* 2023; Yusuf *et al.,* 2023). Additionally, streamlined licensing procedures and clear guidelines for waste-to-energy projects should be established to reduce bureaucratic hurdles. Furthermore, integrating biogas technology into existing national energy policies and development plans can facilitate its integration into the energy mix. Collaboration with international organizations and agencies that specialize in renewable energy can also provide technical expertise and financial support for biogas initiatives.

D. Awareness and capacity building: Increasing awareness about biogas technology and its benefits is essential to drive its adoption. Capacity building programs can train individuals in the operation and maintenance of biogas plants, helping to address the shortage of technical expertise.

E. Infrastructure development: Investments in waste collection and transportation infrastructure are needed to ensure a consistent supply of organic waste to biogas plants. This includes addressing challenges related to waste sorting and disposal, as well as the development of grid connectivity in remote areas.

F. Financial support: Encouraging financial institutions to offer favorable loans and grants for biogas projects can mitigate the initial investment costs associated with biogas plant construction.

G. Research and development: Research and development (R&D) initiatives are pivotal in advancing biogas technology and its applications. Investments in R&D can lead to the discovery of novel microbial strains that are more efficient in biogas production, as well as the development of pretreatment methods that improve the biodegradability of recalcitrant waste materials (Kor-Bicakci and Eskicioglu, 2019; Maciel-Silva *et al.*, 2019; Zhao *et al.*, 2021; Vyas *et al.*, 2022; Maria *et al.*, 2023; Otieno *et al.*, 2023; Yang *et al.*, 2023; Yue *et al.*, 2023). Furthermore, research efforts should focus on optimizing the operation and control of biogas plants, enhancing process monitoring techniques, and exploring new uses for biogas byproducts, such as digestate, which can serve as a valuable organic fertilizer. Collaboration between academic institutions, government agencies, and private enterprises can foster a vibrant research ecosystem and accelerate the adoption of cutting-edge biogas technologies in Nigeria.

CONCLUSION

This review shows that biogas production in Nigeria offers multifaceted benefits that can contribute to the country's energy security, waste management, and climate change mitigation efforts. By harnessing organic waste for biogas production, Nigeria can diversify its energy sources, reducing reliance on fossil fuels and mitigating the impacts of energy supply fluctuations. Moreover, biogas technology provides an environmentally friendly approach to waste management, converting organic waste into valuable biogas and organic fertilizers, thereby reducing landfill usage and associated environmental pollution. The significance of biogas production in climate change mitigation cannot be overemphasized, as it significantly reduces methane emissions, a potent greenhouse gas emitted when organic waste decomposes in landfills. Utilizing biogas as energy source further reduces carbon dioxide emissions, contributing to Nigeria's climate change mitigation goals. For biogas production to achieve long-term sustainability and scalability in Nigeria, several key factors need to be considered. Clear and consistent policies that incentivize biogas investments and provide financial support will encourage the growth of the sector and attract more stakeholders. Continued research efforts and technical innovations are vital to enhance the efficiency of biogas production, improve feedstock digestibility, and explore new applications of biogas byproducts. Building technical expertise and knowledge-sharing platforms are essential to address the shortage of skilled personnel in designing, operating, and maintaining biogas plants. Increasing public awareness of the benefits of biogas technology is crucial to foster support and participation from various stakeholders, including communities, investors, and policymakers. Investment in waste collection and waste-to-energy infrastructure is necessary, especially in rural areas, to facilitate the availability and transportation of feedstock to biogas plants. Moreover, collaboration among government agencies, private sectors, international organizations, and academic institutions can accelerate the development and adoption of biogas technology in Nigeria.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

Ahammad, S.Z. and Sreekrishnan, T.R. (2016). *Biogas: An Evolutionary Perspective in the Indian Context*. In Green Fuels Technology; Green Energy and Technology; Springer: Cham, Switzerland, pp. 431-443. ISBN 978-3-319-30203-44. **[Crossref]**

Ajaero, C. C., Okafor, C. C., Otunomo, F. A., Nduji, N. N., and Adedapo, J. A. (2023). Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria. *Clean Technologies and Recycling*, 3(1), 44-65. **[Crossref]**

Akinbomi J., Brandberg, T., Sanni, S. A., and Taherzadeh, M. J. (2014). "Development and dissemination strategies for accelerating biogas production in Nigeria," *BioResources* 9(3), 5707-5737.

Amoo, A. O., Ahmed, S., and Haruna, A. (2023). Combinatorial Effect of Process Parameters on the Rate of Biogas Production and Rate of Substrate Degradation Following Anaerobic Digestion of Food Waste and Rumen Content. *Journal of Applied Sciences and Environmental Management*, 27(3), 449-455. [Crossref]

Ampese, L. C., Sganzerla, W. G., Ziero, H. D. D., Mudhoo, A., Martins, G., and Forster-Carneiro, T. (2022). Research progress, trends, and updates on anaerobic digestion technology: A bibliometric analysis. *Journal of Cleaner Production*, 331, 130004. [Crossref]

Anukam, A., Mohammadi, A., Naqvi, M., and Granström, K. (2019). A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency. *Processes*, 7(8), 504. [Crossref]

Anyaoha, K. E., and Zhang, L. (2023). Technology-based comparative life cycle assessment for palm oil industry: the case of Nigeria. *Environment, Development and Sustainability*, 25(5), 4575-4595. [Crossref]

Aworanti, O. A., Agbede, O. O., Agarry, S. E., Ajani, A. O., Ogunkunle, O., Laseinde, O. T. and Fattah, I. M. R. (2023). Decoding Anaerobic Digestion: A Holistic Analysis of Biomass Waste Technology, *Process* Kinetics, and Operational Variables. Energies, 16(8), 3378. [Crossref]

Babatola, J. O., Olotu, O., Awode, A., and Adelodun, A. (2023). Effects of using *P. juliflora* leaves as additive in anaerobic digestion of poultry wastes. *Global Sustainability Research*, 2(2), 58-70. [Crossref]

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S., and Iyyappan, J. (2018). Biogas production-A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and sustainable Energy Reviews*, 90(April), 570-582. [Crossref]

Bhatt, A. H., and Tao, L. (2020). Economic perspectives of biogas production via anaerobic digestion. *Bioengineering*, 7(3), 74. [Crossref]

Bijarchiyan, M., Sahebi, H., and Mirzamohammadi, S. (2020). A sustainable biomass network design model for bioenergy production by anaerobic digestion technology: using agricultural residues and livestock manure. *Energy, Sustainability and Society*, 10, 1-17. [Crossref]

Diamantis, V., Eftaxias, A., Stamatelatou, K., Noutsopoulos, C., Vlachokostas, C., and Aivasidis, A. (2021). Bioenergy in the era of circular economy: Anaerobic digestion technological solutions to produce biogas from lipid-rich wastes. *Renewable Energy*, 168, 438-447. [Crossref]

Dickson, E. M., Hastings, A., and Smith, J. (2023). Energy production from municipal solid waste in low to middle income countries: a case study of how to build a circular economy in Abuja, Nigeria. *Frontiers in Sustainability*, 4, 1173474. [Crossref]

Ekwenna, E. B., Wang, Y., and Roskilly, A. (2023). Bioenergy production from pretreated rice straw in Nigeria: An analysis of novel three-stage anaerobic digestion for hydrogen and methane cogeneration. *Applied Energy*, 348, 121574. [Crossref]

Guardian Newspaper (2019). Lagos abattoir converts cow waste to biogas, https://guardian.ng/property/lagos-abattoir-converts-cow-waste-to-biogas/ assessed on the 4th December, 2023.

Hassan A., Adeyemi A.I., and Odunayo A.P. (2023). Biogas production from animal and modified oil palm bunch wastes. *FUW Trends in Science & Technology Journal*, 8(2): 94 - 99. Avenam. https://avenamlinks.com/gallery/ assessed on 4th December, 2023.

Iglesias, R., Muñoz, R., Polanco, M., Díaz, I., Susmozas, A., Moreno, A. D. and Ballesteros, M. (2021). Biogas from anaerobic digestion as an energy vector: Current upgrading development. *Energies*, 14(10), 2742. [Crossref]

IITA (2022). IITA Y-SWEP biogas technology: A sustainable energy solution and gateway to more research. Retrieved from https://www.iita.org/news-item/iita-y-swep-biogas-technology-a-sustainable-energy-solution-and-gateway-to-more-research/assessed on 10th December, 2023

Ikpe A.E., Imonitie D.I., Ndon A.E. (2019). Investigation of biogas energy derivation from anaerobic digestion of different local food wastes in Nigeria. *Academic Platform Journal of Engineering and Science*, 7-2, 332-340. [Crossref]

Khanal, S. K., Lu, F., Wong, J. W., Wu, D., and Oechsner, H. (2021). Anaerobic digestion beyond biogas. *Bioresource Technology*, 337, 125378. [Crossref]

Kim, H. G., Lee, D. S., Jang, H. N., and Chung, T. H. (2010). Anaerobic digestion technology for biogas production using organic waste. *Journal of the Korea Organic Resources Recycling Association*, 18(3), 50-59.

Kor-Bicakci, G., and Eskicioglu, C. (2019). Recent developments on thermal municipal sludge pretreatment technologies for enhanced anaerobic digestion. *Renewable and Sustainable Energy Reviews*, 110, 423-443. [Crossref]

Kumar, A., and Samadder, S. R. (2020). Performance evaluation of anaerobic digestion technology for energy recovery from organic fraction of municipal solid waste: A review. *Energy*, 197, 117253. [Crossref]

Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P. L. and Tsang, D. C. (2021). A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. *Journal of Cleaner Production*, 305, 127143. [Crossref]

Kunatsa, T., and Xia, X. (2022). A review on anaerobic digestion with focus on the role of biomass codigestion, modelling and optimization on biogas production and enhancement. *Bioresource Technology*, 344, 126311. [Crossref]

Li, R., Fan, X., Jiang, Y., Wang, R., Guo, R., Zhang, Y., and Fu, S. (2023). From Anaerobic Digestion to Single Cell Protein Synthesis: A Promising Route Beyond Biogas Utilization. *Water Research*, 120417. [Crossref]

Maciel-Silva, F. W., Mussatto, S. I., and Forster-Carneiro, T. (2019). Integration of subcritical water pretreatment and anaerobic digestion technologies for valorization of açai processing industries residues. *Journal of cleaner production*, 228, 1131-1142. [Crossref]

Maria, M. P., Torres, N. H., Nascimento, V. R. S., Chagas, T. S. A., Saratale, G. D., Mulla, S. I., and Ferreira, L. F. R. (2023). Current advances in the brewery wastewater treatment from anaerobic digestion for biogas production: A systematic review. *Environmental Advances*, 100394. [Crossref]

Masebinu, S. O., Akinlabi, E. T., Muzenda, E., and Aboyade, A. O. (2019). A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. *Renewable and Sustainable Energy Reviews*, 103, 291-307. [Crossref]

Messineo, A., Maniscalco, M. P., and Volpe, R. (2020). Biomethane recovery from olive mill residues through anaerobic digestion: A review of the state-of-the-art technology. *Science of the Total Environment*, 703, 135508. [Crossref]

Nwoke, O. A., Okeke, C., Chukwuma, E., Ime, C., Ulasi, G., Echiegu, E., and Omah, A. (2023). Effect of ground insulation and feed stock on performance of fixed dome biogas digester. *Agricultural Engineering International: CIGR Journal*, 25(2).

Obileke, K., Nwokolo, N., Makaka, G., Mukumba, P., and Onyeaka, H. (2021). Anaerobic digestion: Technology for biogas production as a source of renewable energy-A review. *Energy & Environment*, 32(2), 191-225. [Crossref]

O'Connor, S., Ehimen, E., Pillai, S. C., Black, A., Tormey, D., and Bartlett, J. (2021). Biogas production from small-scale anaerobic digestion plants on European farms. *Renewable and Sustainable Energy Reviews*, 139, 110580. [Crossref]

Ofomatah, A. C., Okoro, G. I., Ezekoye, V. A., Agbogu, A., and Ezekoye, D. (2023). *The effects of catalyst and codigestion on the performance of biogas yield*. In IOP Conference Series: Earth and Environmental Science (Vol. 1178, No. 1, p. 012014). IOP Publishing. [Crossref]

Ore, O. T., Akeremale, O. K., Adeola, A. O., Ichipi, E., and Olubodun, K. O. (2023). Production and kinetic studies of biogas from anaerobic digestion of banana and cassava wastes. *Chemistry Africa*, 6(1), 477-484. [Crossref]

Otieno, E. O., Kiplimo, R., and Mutwiwa, U. (2023). Optimization of anaerobic digestion parameters for biogas production from pineapple wastes codigested with livestock wastes. *Heliyon*, 9(3). [Crossref]

Ozigis I.I., Oodo S.O. and Lawal N.M. (2019). Design of an anaerobic digester for generation of biogas fired in a burner and lamp. *FUOYE Journal of Engineering and Technology*, 4: 2579-0625 (Online), 2579-0617 (Paper). [Crossref]

Pramanik, S. K., Suja, F. B., Zain, S. M., and Pramanik, B. K. (2019). The anaerobic digestion process of biogas production from food waste: Prospects and constraints. *Bioresource Technology Reports*, 8, 100310. [Crossref]

Rasapoor, M., Young, B., Brar, R., Sarmah, A., Zhuang, W. Q., and Baroutian, S. (2020). Recognizing the challenges of anaerobic digestion: Critical steps toward improving biogas generation. *Fuel*, 261, 116497. **[Crossref]**

Riagbayire, F., and Nayem, Z. (2023). Biogas: An Alternative Energy Source for Domestic and Small-Scale Industrial Use in Nigeria. *American Journal of Innovation in Science and Engineering*, 2(1), 8-16. **[Crossref]**

Singh, R., Hans, M., Kumar, S., and Yadav, Y. K. (2023). Thermophilic Anaerobic Digestion: An Advancement towards Enhanced Biogas Production from Lignocellulosic Biomass. *Sustainability*, 15(3), 1859. **[Crossref]**

Subbarao, P. M., D'Silva, T. C., Adlak, K., Kumar, S., Chandra, R., and Vijay, V. K. (2023). Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy. *Environmental Research*, 116286. **[Crossref]**

Thompson, T. M., Young, B. R., and Baroutian, S. (2020). Efficiency of hydrothermal pretreatment on the anaerobic digestion of pelagic Sargassum for biogas and fertilizer recovery. *Fuel*, 279, 118527. **[Crossref]**

Uddin, M. N., Siddiki, S. Y. A., Mofijur, M., Djavanroodi, F., Hazrat, M. A., Show, P. L. and Chu, Y. M. (2021). Prospects of bioenergy production from organic waste using anaerobic digestion technology: a mini review. *Frontiers in Energy Research*, 9, 627093. **[Crossref]**

Vyas, S., Prajapati, P., Shah, A. V., Srivastava, V. K., and Varjani, S. (2022). Opportunities and knowledge gaps in biochemical interventions for mining of resources from solid waste: a special focus on anaerobic digestion. *Fuel*, 311, 122625. **[Crossref]**

Wainaina, S., Awasthi, M. K., Sarsaiya, S., Chen, H., Singh, E., Kumar, A. and Taherzadeh, M. J. (2020). Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. *Bioresource Technology*, 301, 122778. **[Crossref]**

Yang, S., Luo, F., Yan, J., Zhang, T., Xian, Z., Huang, W. and Huang, L. (2023). Biogas production of food waste with in situ sulfide control under high organic loading in two-stage anaerobic digestion process: Strategy and response of microbial community. *Bioresource Technology*, 373, 128712. **[Crossref]**

Yao, Y., Huang, G., An, C., Chen, X., Zhang, P., Xin, X. and Agnew, J. (2020). Anaerobic digestion of livestock manure in cold regions: Technological advancements and global impacts. *Renewable and Sustainable Energy Reviews*, 119, 109494. **[Crossref]**

Yue, T., Liu, T., Chu, X., Zheng, G., Wang, M., and Sun, Y. (2023). Effects of biogas slurry reflux mode and reflux rate on methane production by mixed anaerobic digestion of corn straw and pig manure. *Journal of Cleaner Production*, 411, 137214. **[Crossref]**

Yusuf, A. A., Abubakar, A. M., Wali, S. A., and Ngulde, A. B. (2023). Comparison of the First Order and Modified First-Order Model for Biogas Production from Chicken Manure in Maiduguri, Borno State of Nigeria. *International Journal of Scientific and Multidisciplinary Research*, 1(2): 73-78. **[Crossref]**

Zanna, M. W., and Jatto, M. A. (2023). An Enhanced Biogas Production from Organic Waste and Biotech Culture. *Fane-Fane International Multi-Disciplinary Journal*, 7(1, June), 8-16.

Zhao, W., Yang, H., He, S., Zhao, Q., and Wei, L. (2021). A review of biochar in anaerobic digestion to improve biogas production: performances, mechanisms and economic assessments. *Bioresource Technology*, 341, 125797. **[Crossref]**