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Assessing Potential of Biogas: Harnessing Sustainable Energy from Biomass for Renewable Solutions

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ABSTRACT

This systematic review evaluates the potential of biogas as a sustainable energy source derived from biomass for renewable solutions. Biogas production involves the anaerobic digestion of organic materials, such as agricultural residues, municipal solid waste, and livestock manure, to generate methane-rich gas for electricity generation, heat production, and transportation fuel. The systematic review study comprehensively examines various aspects of biogas, including its production process, environmental benefits, economic viability, technical considerations, challenges, social impacts, circular economy principles, technological innovations, public perception, policy recommendations, and alignment with global climate goals and Sustainable Development Goals. Key findings indicate that biogas offers significant potential to mitigate greenhouse gas emissions, reduce organic waste pollution, promote sustainable agriculture, and create economic opportunities. However, challenges such as technological limitations, financial constraints, and policy barriers impede the widespread adoption of biogas. Policy recommendations emphasize the importance of supportive regulatory frameworks, incentive programs, and international cooperation to facilitate biogas development. Overall, this systematic review provides understanding into the role of biogas in advancing renewable energy solutions and underscores the need for concerted efforts to realize its full potential in combating climate change and promoting sustainable development.

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1. Introduction

Future renewable energy systems will need energy storage to maintain equilibrium, particularly if surplus solar and wind energy needs to be used right away. Methane and methanol are examples of carbon-based energy carriers that are carbon dioxide-neutral when biogas is used as a carbon [1]. Fossil resource depletion, non-renewability, rising petroleum fuel costs, and emissions from burning fossil fuels all push energy planners and policy makers to shift their attention to structural studies, alter their energy sources, and switch to cleaner fuels [2]. Using the energy from biomass sources, such biogas, is one of the better solutions in this respect. Among the primary energy sources, biogas may be used directly to generate electricity and heat. It's also a viable alternative for internal combustion generators, micro-turbines, fuel cells, and other power-producing equipment [3].

Biogas is an environmentally friendly power source delivered through the anaerobic processing of natural matter like rural waste, creature fertilizer, and sewage. It essentially comprises of methane (CH4) and carbon dioxide (CO2), with follow measures of different gases. This cycle happens in a controlled climate, regularly inside biogas digesters, where microorganisms separate the natural material without any oxygen [4]. Biogas is a flexible sustainable power source that holds huge commitment in tending to the double difficulties of energy security and ecological maintainability. Saddling the regular disintegration of natural matter, biogas creation offers a maintainable option in contrast to petroleum derivatives, moderating ozone depleting substance discharges and adding to the roundabout economy. One of the most convincing benefits of biogas lies in its natural advantages [5]. Through anaerobic processing, natural waste like agrarian buildups, creature compost, and food scraps can be changed over into biogas, lessening methane discharges from deterioration and landfills. As indicated by [6], biogas creation from natural waste can essentially moderate ozone harming substance discharges, offering a low-carbon option in contrast to conventional energy sources. Moreover, biogas digestate, a result of the assimilation cycle, fills in as a supplement rich manure, advancing soil wellbeing and decreasing the requirement for engineered composts [7].

In addition to its environmental advantages, biogas presents compelling economic opportunities. Studies have shown that biogas production can generate revenue streams from waste management and energy sales [8]. Moreover, government incentives and policies supporting renewable energy adoption further enhance the economic viability of biogas projects [9]. Valorizing organic waste and producing renewable energy, biogas offers a cost-effective solution for both waste management and energy generation. Beyond its environmental and economic dimensions, biogas implementation has significant social implications [10]. In rural areas and developing countries, biogas digesters provide access to clean energy for cooking, heating, and lighting, improving indoor air quality and reducing reliance on traditional biomass fuels [11]. Furthermore, biogas projects create employment opportunities and empower local communities, fostering sustainable development and poverty alleviation. Addressing energy poverty and promoting social inclusion, biogas contributes to the achievement of multiple Sustainable Development Goals.

The potential of biogas aligns closely with several Sustainable Development Goals (SDGs), making it a vital contributor to global sustainability efforts. Biogas production addresses SDG 7 (Affordable and Clean Energy) by providing a renewable alternative to fossil fuels, thereby promoting energy access and reducing greenhouse gas emissions [12]. Moreover, biogas projects contribute to SDG 13 (Climate Action) by mitigating methane emissions from organic waste decomposition and landfills [13]. Biogas also intersects with SDG 12 (Responsible Consumption and Production) by promoting circular economy principles through the valorization of organic waste and the production of nutrient-rich digestate for agriculture [14]. Furthermore, biogas implementation supports SDG 8 (Decent Work and Economic Growth) by creating employment opportunities, particularly in rural areas and developing countries [15]. Additionally, biogas projects address SDG 3 (Good Health and Well-being) by reducing indoor air pollution associated with traditional biomass fuels, thereby improving public health outcomes [16].

The motivation for conducting a systematic literature review on the potential of biogas lies in addressing the growing demand for sustainable energy solutions amidst concerns over climate change and environmental degradation. Biogas, derived from organic waste through anaerobic digestion, offers a renewable alternative to fossil fuels, with significant environmental, economic, and social benefits. However, despite its potential, there are gaps in the existing literature that warrant further investigation. For instance, studies by [17,18] highlight challenges and prospects in biogas production, indicating gaps in understanding the technical limitations and policy barriers hindering its widespread adoption. Additionally, research by [19] underscores the need to explore the socio-economic impacts of biogas implementation, particularly in rural areas and developing countries.

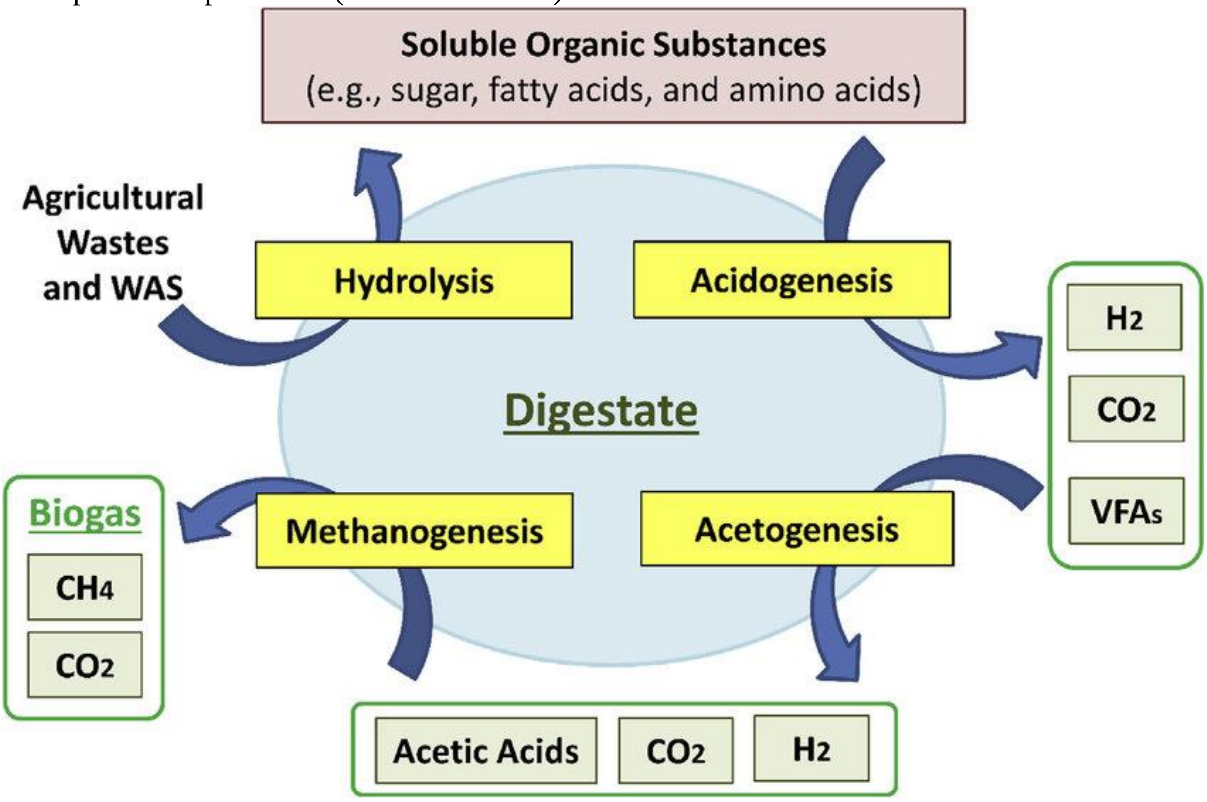
Furthermore, while some studies focus on the environmental benefits of biogas, such as its contribution to greenhouse gas mitigation [20], others emphasize its economic viability and potential revenue streams [21]. However, there is a lack of comprehensive synthesis that integrates these perspectives and evaluates the overall potential of biogas as a renewable energy solution. Thus, this systematic literature review aims to fill these gaps by providing a holistic assessment of the potential of biogas, considering its environmental, economic, and social dimensions, and identifying avenues for future research and policy intervention.

2. Overview of Biogas Production

Biogas production is a sustainable process that involves the anaerobic digestion of organic matter to generate a renewable energy source. The process of biogas production begins with the collection and preprocessing of organic feedstock. Various biomass sources can be utilized, including agricultural residues, livestock manure, food waste, sewage sludge, and energy crops such as maize or switchgrass [22]. These feedstocks are loaded into a biogas digester, where anaerobic microorganisms break down the organic matter in the absence of oxygen. This biological decomposition process produces biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2), along with small amounts of other gases such as hydrogen sulfide (H_2S) and ammonia (NH_3) [23,24].

The different types of biogas digesters correspond to the phases of anaerobic digestion (AD). For instance, batch digesters can be likened to the hydrolysis phase, where organic matter is broken down into simpler compounds. Continuous stirred-tank digesters (CSTs) align with the acidogenesis phase, where acids are produced from the breakdown of complex molecules [25]. Plug flow digesters can be related to acetogenesis, where acetate and other volatile fatty acids are generated. Lastly, anaerobic lagoons can be associated with methanogenesis, the phase where methane gas is produced. Just as each digester type has its strengths and weaknesses, each phase of anaerobic digestion plays a crucial role in the overall process, contributing to the efficient conversion of organic waste into valuable biogas [26].

The four phases of a typical naerobic diges-tion (AD) process—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—are simplified and shown in Figure 1. Water vapor (H2O), siloxanes, H_2S, H_2, CH_4, CO_2, and other gases are all mixed together in the biogas that is generated [27,28]. The efficiency and output of biogas production are influenced by various factors, including feedstock composition, temperature, pH, retention time, and digester design. The composition of organic feedstock plays a crucial role in biogas yield, with high-carbon materials such as crop residues and energy crops typically producing more methane than nitrogen-rich substrates like manure or food waste [29]. Optimal temperature and pH conditions are also essential for maintaining microbial activity and biogas production rates. Mesophilic temperatures (around 35-40°C) are suitable for most biogas digesters, although thermophilic conditions (around 50-60°C) can enhance digestion efficiency and pathogen reduction [30].



Source: Pan et al (2021)

Figure 1. Process-wise stages of biogas production

Retention time, or the duration of organic matter digestion within the digester, influences biogas production kinetics and process stability. Longer retention times allow for more extensive substrate degradation and methane production but may require larger digester volumes and longer operational cycles. Digester design and mixing mechanisms affect the distribution of organic matter and microbial activity within the digester, influencing biogas production efficiency and process stability [31]. Proper mixing ensures uniform substrate contact with microorganisms and prevents the accumulation of solids, which can inhibit digestion and reduce biogas yields.

3. Environmental Benefits of Biogas

The environmental benefits of biogas are broad, encompassing its role in greenhouse gas emissions reduction, organic waste mitigation, sustainable agriculture, anaerobic digestion, methane capture, digestate fertilizer, renewable energy, climate change mitigation as depicted in Figure 2. Firstly, biogas plays a crucial role in reducing greenhouse gas emissions, particularly methane (CH4), which is a potent greenhouse gas with a much higher global warming potential than carbon dioxide (CO2). Through anaerobic digestion, biogas production captures methane that would otherwise be released into the atmosphere during the decomposition of organic waste in landfills or agricultural settings. According to [32], biogas production from organic waste can significantly mitigate methane emissions, thereby helping to mitigate climate change and its associated impacts.

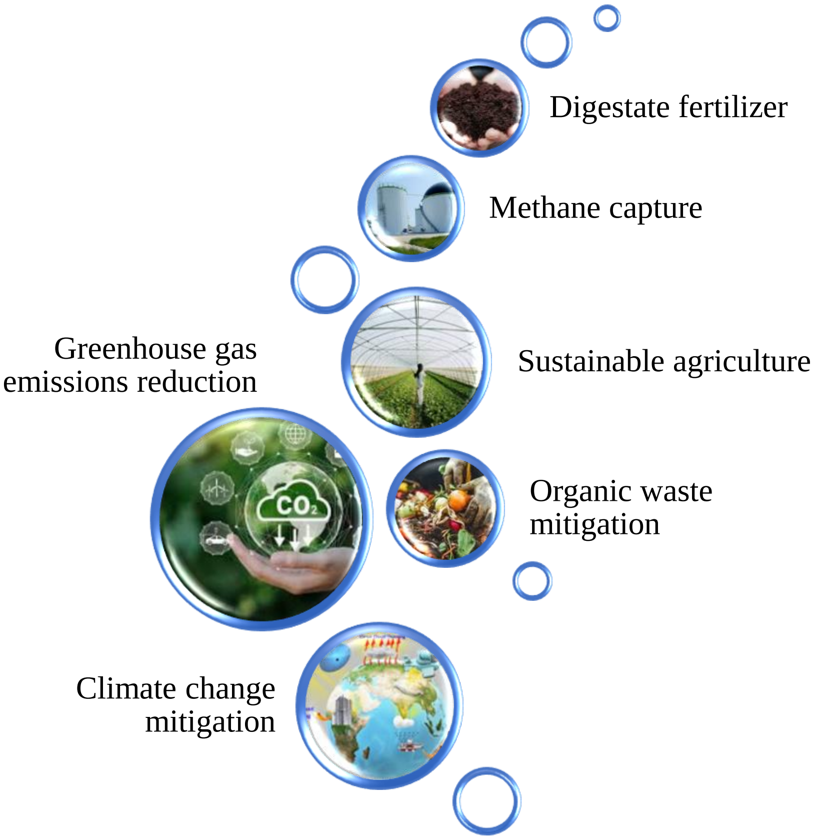


Figure 2: Environmental Benefits of Biogas

Secondly, biogas production contributes to the mitigation of organic waste pollution by diverting organic waste streams from landfills and other disposal sites. Organic waste, such as agricultural residues, food scraps, and livestock manure, can emit methane and other harmful gases as it decomposes anaerobically. By diverting this waste into biogas digesters, organic matter is effectively converted into biogas and nutrient-rich digestate, reducing the environmental burden of organic waste pollution [33,34]. Furthermore, biogas production contributes to sustainable agriculture by producing digestate, a nutrient-rich fertilizer that can be used to improve soil health and fertility. The digestate generated during the biogas production process contains valuable nutrients such as nitrogen, phosphorus, and potassium, which are essential for plant growth and crop production. By returning these nutrients to the soil, digestate helps to replenish soil fertility, reduce the need for synthetic fertilizers, and promote sustainable agricultural practices [35-37].

In addition to these environmental benefits, biogas production also offers social and economic advantages, including job creation, rural development, and energy access for marginalized communities [38]. By harnessing the energy potential of biomass and organic waste, biogas provides a decentralized and renewable energy source that can contribute to energy security and resilience in both rural and urban settings.

4. Economic Viability of Biogas

The economic viability of biogas as a renewable energy source is a critical aspect of its adoption and widespread implementation. This section covered key dimensions of the economic viability of biogas, including its cost-effectiveness compared to fossil fuels, its potential for revenue generation from waste management, and the role of government incentives and policies in supporting biogas production as summarized in Figure 3. Biogas offers significant cost-effectiveness compared to fossil fuels, particularly in the context of rising energy prices and the external costs associated with climate change and environmental degradation. While the initial investment costs for biogas infrastructure may be higher than traditional energy sources, such as coal or natural gas, the long-term operational costs are generally lower, especially when considering the potential for revenue generation from waste management [39,40]. Moreover, biogas production provides a reliable and stable source of energy, less susceptible to price volatility and geopolitical risks associated with fossil fuel extraction and transportation.

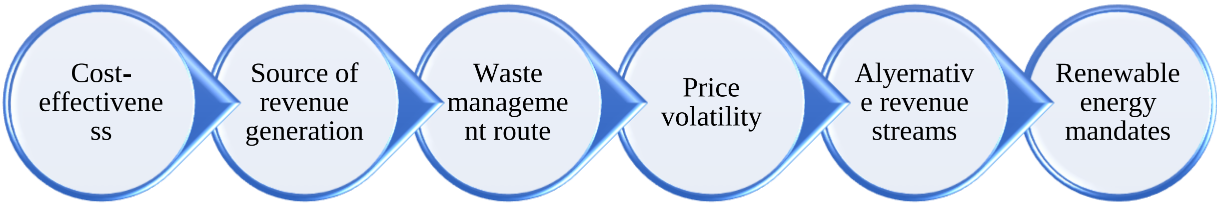


Figure 3: Economic viability of biogas as a renewable energy source

Biogas presents considerable potential for revenue generation from waste management. By diverting organic waste streams from landfills and other disposal sites, biogas production not only reduces waste management costs but also creates opportunities for revenue generation through the sale of biogas and digestate fertilizer [41]. Biogas can be used for various applications, including electricity generation, heating, and transportation fuel, providing a versatile and valuable commodity in energy markets. Additionally, the digestate produced during the biogas production process serves as a nutrient-rich fertilizer, which can be sold or used to improve soil health and agricultural productivity, further enhancing the economic value of biogas production [42, 43].

Government incentives and policies play a crucial role in supporting the economic viability of biogas production. Many governments around the world offer financial incentives, tax credits, and subsidies to promote renewable energy development and reduce greenhouse gas emissions. These incentives can include feed-in tariffs, renewable energy credits, grants, and low-interest loans for biogas projects [44]. Additionally, regulatory frameworks such as renewable energy mandates, carbon pricing mechanisms, and emissions trading schemes create market incentives for biogas producers to participate in renewable energy markets and contribute to climate change mitigation efforts.

5. Technical Considerations in Biogas Production

Technical considerations play a crucial role in the successful implementation of biogas production systems. There are several types of biogas digesters used in practice, each with its advantages and limitations. One common type is the continuous stirred-tank digester (CST), which features a continuously stirred tank to maintain uniform temperature and mixing of organic feedstock. CST digesters are suitable for large-scale operations and offer consistent biogas production rates. Another type is the plug flow digester, which operates in a continuous flow manner, with organic matter flowing through the digester in one direction. Plug flow digesters are more suited for batch feeding and are often used in agricultural settings. Additionally, there are fixed dome digesters, which consist of a sealed, dome-shaped container that captures biogas produced during anaerobic digestion. Fixed dome digesters are simple and cost-effective but may require regular maintenance to ensure gas tightness and optimal performance [45].

The technique for estimation of how much energy produced from biogas was accounted for by [46]. The assembling unit, which consumes biomass or biogas along with different powers and the energy delivered from environmentally friendly power sources are named a piece of the power or intensity comparing to the portion of the substance energy in biomass or biogas fuel synthetic energy consumed in the creation of energy, determined based on the calorific worth of the fuel, as per Equation 1:

$$E_{OZE} = \left(\frac{\sum_{i=1}^{n} M_{Bi} W_{Bi}}{\sum_{i=1}^{n} M_{Bi} W_{Bi} + \sum_{j=1}^{m} M_{Kj} W_{Kj}} \right) \qquad (1)$$

where:

E_{OZE} – the amount of electricity or heat from renewable energy sources, (MWh, GJ)

E – the amount of electricity or heat produced in a generating unit, which combusts biomass or biogas together with other fuels, (MWh, GJ)

M_{Bi} – amount of biomass or biogas, burned in the generating unit, (Mg)

M_{Kj} – amount of fuel other than biomass or biogas combusted in the generating unit, (Mg) W_{Bi} – calorific value of biomass or biogas burned in a generating unit, (MJ·Mg-1)

W_{Kj} – calorific value of fuel other than biomass or biogas combusted in the generating unit, (MJ·Mg-1)

n – the number of types of biomass or biogas burned in a generating unit,

m – the number of types of fuels other than biomass or biogas, burned in the generating unit.

Optimizing biogas production efficiency involves several factors, including feedstock selection, digester design, temperature control, and retention time. High-quality feedstock with a balanced carbon-to-nitrogen ratio and adequate moisture content is essential for maximizing biogas yields [47]. Digester design plays a critical role in promoting efficient mixing of organic matter and microbial activity, ensuring thorough digestion and gas production. Maintaining optimal temperature conditions, typically mesophilic (around 35-40°C) or thermophilic (around 50-60°C), is crucial for maximizing microbial activity and biogas production rates [48]. Longer retention times allow for more extensive substrate degradation and methane production but may require larger digester volumes and longer operational cycles. Additionally, monitoring and controlling key process parameters, such as pH, alkalinity, and volatile fatty acid concentrations, help to maintain process stability and prevent digester upset [49].

Safari et al. [50] used 29 bioreactors across three temperature clusters to optimize biochemical methane production. Design-Expert 8.0 software determined the best parameters for maximum methane yield, considering temperature, stirring time, TS, and Inoculum ratio. They employed the Box-Behnken design with variables at three levels (-1, 0, +1) and methane yield (L.kg-1VS) as the response. Twenty-nine experiments with five center point replications were conducted. A second-order polynomial model, assessed via ANOVA and R^2, depicted parameter interactions influencing methane production. Basically, the process involves execution of statistically designed experiments, estimation of model coefficients and response prediction followed by model adequacy evaluation. An empirical model was developed to correlate the response based on second order quadratic model of equation (2):

$$V_i = C_O + \sum_{i=1}^{n} C_i\, A + \sum_{i=0}^{n} C_{ii}\; A_i^2 + \sum_{i=1}^{n}\sum_{i=i+1}^{n} C_{ij} A\, B_j + \varepsilon \qquad (2)$$

Where V_i is the predicted response, C_o is the constant coefficient, C_i the linear coefficients, C_{ii} is the quadratic coefficients, C_{ij} is the interactive coefficients, A_i and B_j are the coded values of the variables, n is the number of independent test variables and ε is the random error [51]. This approach facilitated optimizing methane gas production from canola residues, cattle manure, and inoculums.

Biogas production systems face various maintenance and operational challenges that can impact system performance and reliability. Common challenges include digester fouling, gas leaks, foaming, and odour issues [52]. Digester fouling occurs when organic matter accumulates and forms solids deposits, reducing mixing efficiency and gas production rates. Gas leaks can occur due to deteriorating seals or structural damage to the digester, leading to loss of biogas and potential safety hazards. Foaming is another common issue caused by excessive gas production or microbial activity, which can disrupt digester operations and reduce gas quality. Odour issues may arise from incomplete digestion or improper management of organic feedstock, leading to nuisance odours and community complaints [53].

6. Bibliometric Analysis

6.1 *Publication Trends*

In recent years, there has been a notable increase in the publication of research articles focused on assessing the potential of biogas as a sustainable energy source derived from biomass [54,55]. This surge in publications reflects the growing recognition of biogas as a viable alternative to fossil fuels and the increasing urgency to mitigate climate change and transition towards renewable energy sources. Researchers and policymakers alike have shown keen interest in understanding the technical, economic, and environmental aspects of biogas production, leading to a steady rise in scholarly output in this field.

Numerous factors contribute to the observed publication trends. Advancements in biogas production technologies, such as improved anaerobic digestion processes and novel reactor designs, have spurred research efforts aimed at optimizing biogas yields and enhancing process efficiency [55]. Additionally, the recognition of biogas as a versatile energy source with applications in electricity generation, heat production, and transportation fuels has fueled interest from both academia and industry. Moreover, the pressing need to address waste management challenges and reduce greenhouse gas emissions has prompted increased research funding and collaboration in the field of biogas production and utilization [56]. The publication trends reflect a growing awareness of the potential of biogas to contribute to sustainable energy solutions and address pressing environmental challenges.

6.2 *Keyword Frequencies and Emerging Themes*

Analysis of keyword frequencies provides valuable understanding into the core themes and emerging trends within the literature on biogas potential assessment. Key keywords commonly found in research articles include "biogas," "sustainable energy," "biomass," "renewable energy," and "waste management." These keywords reflect the broad nature of biogas production and its significance in the context of renewable energy and environmental sustainability [57].

Emerging themes within the literature encompass various aspects of biogas assessment, including environmental benefits, economic viability, technological innovation, and policy frameworks [58,59]. Research articles often explore the environmental advantages of biogas production, such as methane emission reduction, organic waste diversion, and soil nutrient enrichment. Economic considerations, such as cost-effectiveness compared to fossil fuels and revenue generation from waste management, are also prominent themes in the literature [59, 60]. Technological advancements in biogas production, such as digester optimization and biogas upgrading techniques, are frequently discussed topics, highlighting ongoing efforts to improve process efficiency and performance. Additionally, policy frameworks and regulatory mechanisms governing biogas production and utilization receive significant attention, reflecting the importance of supportive policy environments in driving renewable energy adoption and sustainable development [61, 62].

6.3 *Core Themes and Emerging Trends*

The literature on biogas potential assessment encompasses several core themes and emerging trends that reflect the broad nature of biogas production and its implications for renewable energy and environmental sustainability. Key themes within the literature include environmental benefits, economic viability, technological innovation, and policy frameworks. Environmental benefits of biogas production are a central theme in the literature, with research focusing on methane emission reduction, organic waste diversion, and soil nutrient enrichment [63,64]. Biogas production offers a sustainable solution to organic waste management, reducing greenhouse gas emissions and mitigating environmental pollution.

Economic viability is another prominent theme in the literature, with studies assessing the cost-effectiveness of biogas production compared to fossil fuels and exploring potential revenue streams from waste management [65]. Biogas projects have the potential to generate revenue through the sale of biogas and digestate fertilizer, contributing to economic development and job creation. Technological innovation is a key driver of research in the field of biogas potential assessment, with ongoing efforts to optimize biogas production processes, enhance process efficiency, and develop novel biogas upgrading technologies. Advances in digester design, substrate pretreatment methods, and biogas purification techniques are enabling the expansion of biogas production and utilization [66].

Policy frameworks and regulatory mechanisms governing biogas production and utilization are also significant themes in the literature, with research focusing on the role of government incentives, subsidies, and renewable energy targets in driving renewable energy adoption and promoting sustainable development. Supportive policy environments are essential for overcoming barriers to biogas deployment and scaling up renewable energy deployment. Emerging trends within the literature include a shift towards decentralized biogas production, community-based initiatives, and integration with circular economy principles [67,68]. Community-led biogas projects empower local communities, promote social inclusion, and contribute to sustainable development goals. Integration with circular economy principles involves maximizing resource efficiency and minimizing waste generation throughout the biogas production value chain, creating synergies between energy, agriculture, and waste management sectors.

6.4 *Core Themes and Emerging Trends*

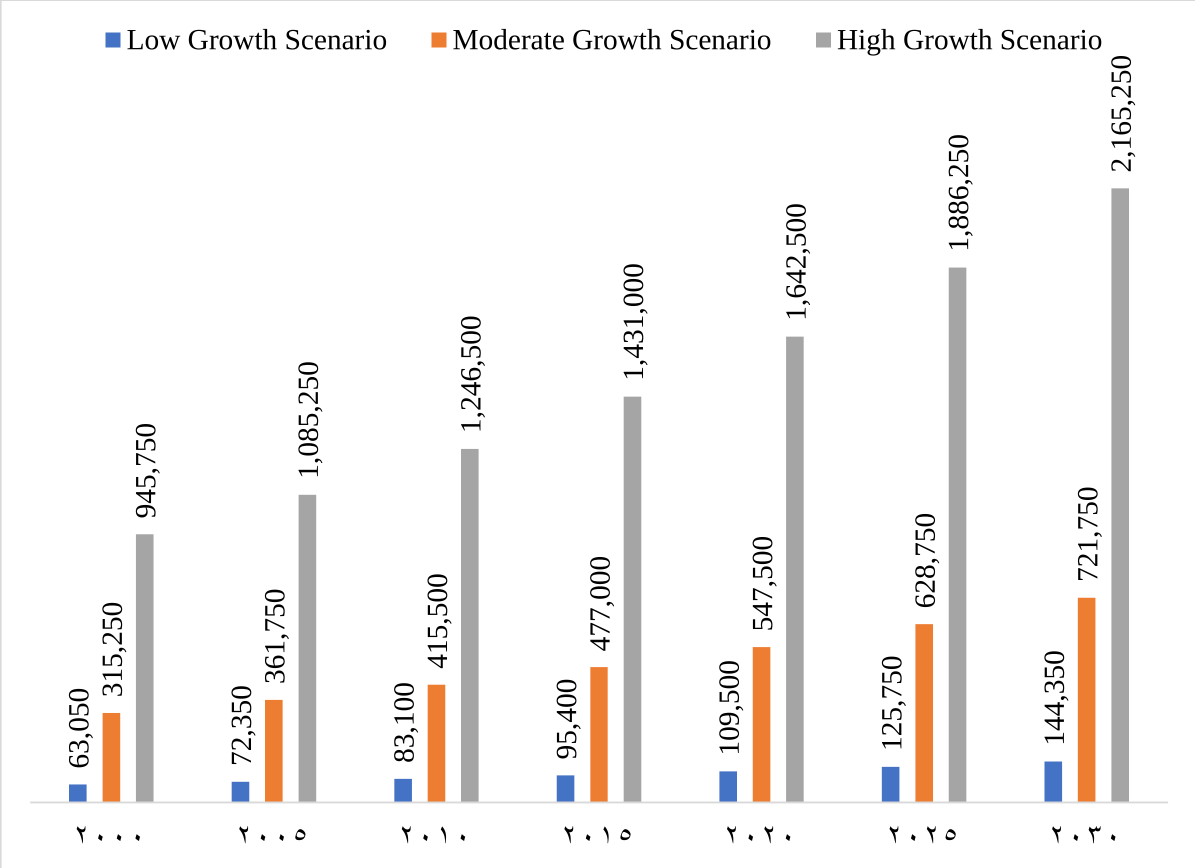
Authorship patterns and collaboration networks provide valuable understanding into the structure and dynamics of research communities within the field of biogas potential assessment. Analysis of authorship patterns reveals trends in collaboration among researchers from diverse disciplinary backgrounds, institutions, and geographic regions. Collaborative research efforts are common in the field of biogas potential assessment, with researchers from academia, industry, government agencies, and non-governmental organizations (NGOs) collaborating to address complex research questions and challenges. Collaboration networks often span multiple disciplines, including environmental science, engineering, agriculture, economics, and policy studies [69,70].

Collaborative research projects and partnerships facilitate knowledge exchange, interdisciplinary collaboration, and capacity building, driving innovation and advancing the state of knowledge in biogas production and utilization. By leveraging complementary expertise and resources, collaborative research endeavors contribute to addressing real-world challenges and informing evidence-based policy and decision-making processes. In addition to academic collaborations, collaborations between researchers and industry stakeholders are common in the field of biogas potential assessment. Industry partnerships enable researchers to access real-world data, infrastructure, and expertise, facilitating technology transfer and commercialization of research outcomes. Industry-academic collaborations also provide opportunities for applied research, technology demonstration, and field testing of innovative biogas production technologies.

7. Social Impacts of Biogas Implementation

The implementation of biogas technology has profound social impacts, ranging from job creation and empowerment of local communities to significant health benefits. Understanding these social impacts is crucial for assessing the broader implications of biogas adoption and its role in sustainable development. One of the most notable social impacts of biogas implementation is job creation. Biogas projects require a range of skilled and unskilled labor for construction, operation, and maintenance, thereby generating employment opportunities in rural and peri-urban areas where these projects are often located. For instance, a study by [71] highlights the employment potential of biogas projects in rural communities, where jobs are created in sectors such as construction, agriculture (for feedstock supply), and biogas plant operation and maintenance. This not only improves livelihoods but also contributes to poverty alleviation and economic development in these regions.

Moreover, biogas implementation empowers local communities by providing them with access to clean and renewable energy resources. By decentralizing energy production and distribution, biogas projects reduce dependency on centralized energy infrastructure and empower communities to manage their energy needs locally. This can have transformative effects on community resilience and self-sufficiency, as illustrated by case studies of community-led biogas initiatives [72,73]. Additionally, the revenue generated from biogas production can be reinvested in community development projects, further enhancing social welfare and cohesion. [74] assumes that the Nigerian energy market with biogas digesters takes off finally in the year 2000 such that the number of biogas digesters in the country between 2000 and 2030 are as given by Figure 4.



Source: Akinbami et al., (2001)

Figure 4: Total number of projected biogas digesters for the country for the period 2000–2030 under different growth scenarios

Figure 4 illustrates the projected total number of biogas digesters for the country from 2000 to 2030, based on low, moderate, and high growth scenarios. Under the low growth scenario, the number of digesters increases gradually over time, while the moderate and high growth scenarios show more rapid expansion. By 2030, the high growth scenario forecasts the highest number of digesters, exceeding 2 million units. These projections highlight the potential growth trajectory of biogas technology adoption, reflecting different rates of adoption and investment in renewable energy infrastructure over the specified period.

Furthermore, the health benefits of biogas implementation are significant, particularly in areas with high levels of indoor air pollution from traditional cooking fuels such as wood, charcoal, and kerosene. Biogas, being a clean-burning fuel, reduces indoor air pollution and associated health risks such as respiratory diseases and eye infections. Studies have shown that the adoption of biogas for cooking can lead to improvements in indoor air quality and reductions in respiratory illnesses among household members [27]. This not only improves the health and well-being of individuals but also reduces healthcare costs and enhances productivity, particularly among women and children who are disproportionately affected by indoor air pollution.

8. Biogas and Circular Economy Principles

Biogas plays a pivotal role in advancing circular economy principles by transforming organic waste into valuable resources, closing nutrient cycles, and integrating with circular economy models. One of the key contributions of biogas to the circular economy is its role in waste valorization. Organic waste streams, such as agricultural residues, food waste, and sewage sludge, are abundant and pose environmental challenges if not managed effectively. Biogas technology offers a sustainable solution by converting these organic wastes into biogas through anaerobic digestion, simultaneously reducing greenhouse gas emissions and producing renewable energy [46]. The residual digestate from the biogas production process serves as a nutrient-rich fertilizer, closing the loop on organic waste management and contributing to soil health and agricultural productivity.

Closing nutrient cycles is another crucial aspect of biogas in the circular economy. By digesting organic waste, biogas plants capture and recycle nutrients such as nitrogen, phosphorus, and potassium, which are essential for plant growth and soil fertility. The digestate produced from biogas production serves as a natural fertilizer, providing a sustainable alternative to chemical fertilizers and reducing reliance on finite mineral resources [4]. This closed-loop nutrient cycle promotes resource efficiency and reduces the environmental impacts associated with conventional agricultural practices, such as nutrient runoff and soil degradation.

Moreover, biogas integration with circular economy models offers synergistic opportunities for resource recovery and value creation. Circular economy principles advocate for the redesign of systems to minimize waste generation and maximize resource utilization through reuse, recycling, and regeneration [6]. Biogas projects can be integrated into circular economy frameworks by co-digesting diverse organic waste streams, implementing nutrient recovery technologies, and exploring symbiotic relationships with other industries [7]. For example, biogas plants can co-locate with agro-industrial facilities to utilize waste heat for digestion and utilize digestate as a feedstock or soil amendment, thereby optimizing resource utilization and enhancing economic viability.

9. Technological Innovations in Biogas Production

Technological innovations in biogas production have significantly advanced the efficiency, reliability, and sustainability of anaerobic digestion processes, biogas upgrading technologies, and integration with smart grid systems. Advances in anaerobic digestion processes have led to improvements in biogas yield, process stability, and feedstock flexibility. Research by [75] highlights innovations such as high-rate anaerobic digestion, co-digestion of diverse feedstocks, and process optimization techniques that enhance biogas production efficiency and reduce operational costs. High-rate anaerobic digestion technologies, such as anaerobic membrane bioreactors and anaerobic sequencing batch reactors, offer advantages in terms of smaller footprint, higher loading rates, and shorter hydraulic retention times, enabling faster biogas production and higher energy yields [11]. Additionally, advancements in pre-treatment methods, such as thermal, chemical, and biological pre-treatment, improve the digestibility of recalcitrant feedstocks and enhance biogas production rates [15].

Biogas upgrading technologies have also undergone significant innovation, enabling the purification and enrichment of biogas to meet quality specifications for injection into natural gas grids or use as transportation fuels. Membrane-based technologies, such as pressure swing adsorption (PSA) and membrane separation, offer advantages in terms of low energy consumption, high selectivity, and scalability [17]. Additionally, biological upgrading methods, such as microbial methanation and carbon dioxide hydrogenation, utilize microbial consortia or catalysts to convert carbon dioxide and hydrogen into methane, thereby increasing the methane content of biogas and improving its energy density [19]. These advancements in biogas upgrading technologies enhance the versatility and marketability of biogas as a renewable energy source, enabling its integration into existing energy infrastructure and facilitating its role in decarbonizing the energy sector.

Integration with smart grid systems represents another frontier of technological innovation in biogas production, enabling enhanced grid stability, demand response, and renewable energy integration. Smart grid technologies, such as advanced metering infrastructure, energy management systems, and grid-connected biogas plants, enable real-time monitoring and control of energy flows, optimizing biogas production and consumption based on grid demand and renewable energy availability [21]. Moreover, biogas plants can serve as distributed energy resources, providing grid services such as frequency regulation, voltage support, and peak shaving through biogas cogeneration, energy storage, and demand-side management strategies [22]. These synergies between biogas production and smart grid systems facilitate the integration of renewable energy sources into the grid, enhance grid resilience, and support the transition to a low-carbon energy future.

10. Challenges and Barriers to Biogas Adoption

Challenges and barriers to biogas adoption present significant hurdles to the widespread deployment and utilization of this renewable energy technology. These challenges and limitation include technological limitations, financial constraints, policy and regulatory hurdles, feedstock variability, high upfront capital costs, long payback periods, regulatory uncertainty as covered in Figure 5.

Technological limitations represent a fundamental challenge to biogas adoption, encompassing issues related to feedstock availability, process efficiency, and system reliability. Research by [76] identifies feedstock variability and substrate complexity as key technological challenges, as different organic waste streams require tailored digestion processes and pre-treatment methods to optimize biogas yield. Additionally, the intermittent nature of biogas production and the susceptibility of anaerobic digestion systems to operational disruptions, such as pH fluctuations, hydraulic overloading, and substrate inhibition, pose challenges to process stability and biogas quality [24].

Financial constraints are another significant barrier to biogas adoption, affecting both project development and operational viability. High upfront capital costs associated with biogas plant construction, infrastructure investment, and equipment procurement often deter potential investors and project developers, particularly in resource-constrained settings [25]. Moreover, the long payback periods and uncertain revenue streams from biogas production pose financial risks and limit access to financing options, such as loans, grants, and subsidies, necessary to fund biogas projects [29]. Without adequate financial support and incentives, biogas projects may struggle to achieve financial viability and attract investment, hindering their scalability and commercialization.

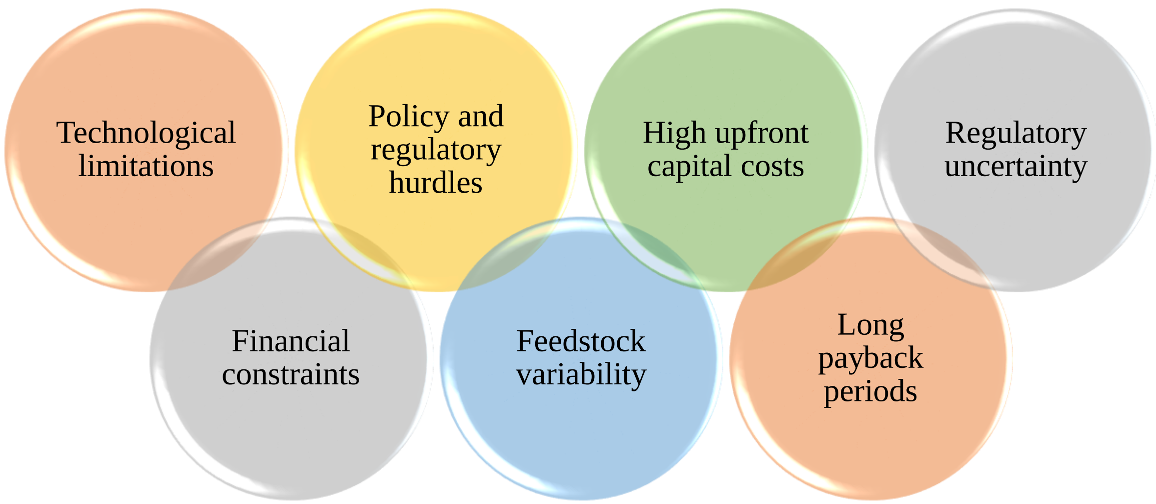


Figure 5: Challenges and Barriers to Biogas Adoption

Policy and regulatory hurdles represent another barrier to biogas adoption, as inconsistent or inadequate policy frameworks can impede market development and investment in renewable energy infrastructure. Research by [31] highlights the importance of supportive policy environments in driving biogas deployment, including feed-in tariffs, renewable energy mandates, tax incentives, and regulatory frameworks that facilitate grid connection and biogas injection. However, the lack of policy coherence, regulatory uncertainty, and bureaucratic delays in permit approvals can create barriers to entry and increase project development costs, discouraging investment in biogas projects [32].

Addressing the challenges and barriers to biogas adoption requires a multi-faceted approach that addresses technological, financial, and policy constraints while fostering collaboration between stakeholders and leveraging innovative solutions. Technological advancements aimed at improving process efficiency, enhancing feedstock flexibility, and optimizing system performance are essential for overcoming technological limitations and increasing the attractiveness of biogas as a renewable energy option [70]. Research and development initiatives focused on innovation in anaerobic digestion processes, biogas upgrading technologies, and smart grid integration can unlock new opportunities for biogas deployment and enhance its competitiveness in the energy market [32].

Moreover, addressing financial constraints requires innovative financing mechanisms, risk-sharing arrangements, and capacity-building initiatives that reduce investment risks and enhance the financial viability of biogas projects. Public-private partnerships, green finance instruments, and crowdfunding platforms offer potential avenues for mobilizing investment and unlocking capital for biogas development, particularly in emerging markets and rural areas [33]. Additionally, policy interventions that provide financial incentives, such as feed-in tariffs, tax credits, and grants, can stimulate private sector investment in biogas projects and accelerate market uptake [38]. Furthermore, policy and regulatory reforms are needed to create an enabling environment for biogas deployment, including streamlined permitting processes, standardized quality and safety regulations, and clear market signals that incentivize investment in renewable energy infrastructure. Coordinated efforts between government agencies, industry stakeholders, and civil society organizations can facilitate policy dialogue, knowledge sharing, and capacity-building initiatives that promote the adoption of biogas and overcome regulatory hurdles.

11. Biogas in the Context of Global Climate Goals

Biogas has emerged as a promising renewable energy source with significant potential to contribute to global climate goals by mitigating greenhouse gas emissions, aligning with Sustainable Development Goals (SDGs), and participating in carbon markets. Biogas contributes to mitigation efforts by reducing greenhouse gas emissions through the displacement of fossil fuels and the utilization of organic waste as a renewable energy feedstock. Research by [41] highlights the environmental benefits of biogas production, including the avoidance of methane emissions from anaerobic decomposition of organic waste in landfills and the substitution of fossil fuels in energy-intensive sectors such as agriculture, transportation, and industry. By capturing methane emissions from organic waste and converting them into biogas through anaerobic digestion, biogas projects mitigate methane emissions, a potent greenhouse gas with a much higher global warming potential than carbon dioxide [42]. Moreover, biogas production offers co-benefits such as improved air quality, reduced reliance on fossil fuels, and enhanced energy security, further contributing to climate change mitigation efforts.

Moreover, biogas has the potential to play a significant role in carbon markets by monetizing emission reductions and promoting climate finance mechanisms that incentivize sustainable development and emission reduction projects. Carbon markets offer opportunities for biogas projects to generate revenue through the sale of carbon credits, also known as carbon offsets, for verified emission reductions achieved through methane mitigation and renewable energy production [47]. Participation in carbon markets provides financial incentives for biogas developers and investors, enhances project viability, and accelerates the deployment of biogas projects worldwide. Furthermore, carbon finance mechanisms such as the Clean Development Mechanism (CDM) and voluntary carbon markets facilitate technology transfer, capacity-building, and knowledge sharing, promoting the diffusion of biogas technology and best practices across regions and sectors [50].

12. Biogas demonstrates alignment with Sustainable Development Goals (SDGs)

Biogas demonstrates alignment with Sustainable Development Goals (SDGs) by addressing various dimensions of sustainable development, thereby contributing to poverty alleviation, enhancing energy access, ensuring food security, and protecting the environment. The United Nations' SDGs serve as a comprehensive framework for addressing global challenges and fostering sustainable development, with biogas playing a significant role in achieving several key goals.

Figure 6: Biogas demonstrates alignment with Sustainable Development Goals (SDGs)

Firstly, biogas contributes to SDG 7 (Affordable and Clean Energy) by providing a sustainable and accessible energy source, particularly in rural and peri-urban areas where energy access is limited. Biogas projects utilize organic waste to produce renewable energy, reducing dependence on traditional fuels and enhancing energy security for underserved populations, facilitating energy access and affordability for communities [78]. Secondly, biogas supports SDG 12 (Responsible Consumption and Production) by promoting resource efficiency and waste reduction. Through diverting organic waste from landfills and utilizing it as feedstock for biogas production, biogas projects mitigate waste pollution and contribute to a circular economy approach to resource management, fostering responsible consumption and production practices [79].

Moreover, biogas contributes to SDG 13 (Climate Action) by mitigating greenhouse gas emissions and combating climate change. Anaerobic digestion processes in biogas projects capture methane emissions from organic waste and convert them into biogas, thereby reducing methane emissions, a potent greenhouse gas, and displacing fossil fuels, advancing efforts towards climate action and environmental sustainability [80]. Additionally, biogas supports SDG 15 (Life on Land) by promoting sustainable land use practices and biodiversity conservation. The utilization of digestate, a byproduct of biogas production, as organic fertilizer improves soil health, enhances agricultural productivity, and reduces reliance on chemical fertilizers, contributing to land restoration and ecosystem preservation, fostering life on land and biodiversity conservation [52].

Furthermore, biogas projects create employment opportunities, particularly in rural and peri-urban areas, thereby contributing to SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth). Jobs in biogas plant operation, maintenance, and feedstock management empower local communities, stimulate economic growth, and alleviate poverty, promoting social equity and economic development [55].

13. Policy Recommendations for Biogas Development

Regulatory frameworks are essential for providing clarity, consistency, and guidance to stakeholders involved in biogas projects. Policymakers should prioritize the development of robust regulatory frameworks that address permitting, licensing, safety standards, and environmental regulations associated with biogas production. Additionally, regulatory frameworks should streamline approval processes and ensure compliance with relevant laws and regulations to reduce bureaucratic hurdles and expedite project implementation [57]. For example, countries like Germany and Denmark have established comprehensive regulatory frameworks for biogas production, which have facilitated the rapid growth of the biogas sector by providing clear guidelines and regulatory certainty to investors and developers [58].

Incentive programs are instrumental in overcoming financial barriers and incentivizing investment in biogas projects. Policymakers should design and implement a range of incentive programs, including feed-in tariffs, renewable energy credits, tax incentives, grants, and low-interest loans, to stimulate demand for biogas and encourage private sector investment [59]. Furthermore, policymakers should consider implementing performance-based incentives that reward biogas producers for achieving specific environmental and social outcomes, such as methane emissions reduction, waste diversion, and job creation [60]. By aligning incentives with policy objectives, governments can maximize the impact of incentive programs and accelerate the transition to a low-carbon, circular economy.

International cooperation is essential for sharing best practices, technology transfer, and capacity-building initiatives to support biogas development on a global scale. Policymakers should prioritize international cooperation through bilateral and multilateral partnerships, knowledge exchange platforms, and collaborative research and development initiatives [61]. International organizations such as the United Nations, World Bank, and International Renewable Energy Agency (IRENA) play a critical role in facilitating international cooperation and supporting biogas development through capacity-building programs, technical assistance, and funding support [62]. Additionally, regional initiatives and networks can promote cross-border collaboration and facilitate the exchange of experiences and lessons learned among countries with similar biogas potential and challenges [63].

14. Conclusion

In conclusion, the assessment of biogas as a sustainable energy source reveals its significant potential to contribute to global efforts in mitigating climate change, promoting sustainable development, and advancing the transition towards renewable energy. Through a comprehensive analysis of biogas production, environmental benefits, economic viability, technical considerations, social impacts, and policy recommendations, several key findings emerge. Firstly, biogas presents a viable alternative to fossil fuels, offering numerous environmental benefits such as the reduction of greenhouse gas emissions, mitigation of organic waste pollution, and contribution to sustainable agriculture. Additionally, biogas demonstrates economic viability through cost-effectiveness compared to fossil fuels, potential revenue generation from waste management, and government incentives supporting biogas production.

Moreover, technical considerations in biogas production, such as the optimization of production efficiency and maintenance challenges, underscore the importance of technological innovation and continuous improvement in biogas systems. Furthermore, social impacts of biogas implementation, including job creation, empowerment of local communities, and health benefits, highlight its role in promoting social equity and economic development. Policy recommendations for biogas development emphasize the need for supportive regulatory frameworks, incentive programs, and international cooperation to create an enabling environment for biogas projects. By addressing regulatory barriers, providing financial incentives, and promoting knowledge sharing and collaboration, policymakers can accelerate the deployment of biogas and unlock its full potential as a renewable energy source.

Looking ahead, the implications for the future of renewable energy are promising. Biogas, along with other renewable energy sources, has the potential to play a crucial role in the global energy transition, diversifying energy sources, reducing dependency on fossil fuels, and achieving climate resilience. However, realizing this potential requires concerted efforts from policymakers, stakeholders, and investors to prioritize investment in renewable energy infrastructure, promote innovation, and scale up deployment of renewable energy technologies.

References

[1] S. O. Akpasi, J. S. Akpan, U. O. Amune, A. A. Olaseinde and S. L. Kiambi, “Methane Advances: Trends and Summary from Selected Studies,” *Methane*, *3*(2), pp. 276-313, 2024.

[2] Y. He, S. Wang and N. Chen, “Mineral rents, natural resources depletion, and ecological footprint nexus in high emitting countries: Panel GLM analysis,” *Resources Policy*, *89*, pp. 104472, 2024.

[3] A. S. Okoh and A. S. Okoh, “Fossil Fuel Exit: Which Way Nigeria?,” *Oil Mortality in Post-Fossil Fuel Era Nigeria: Beyond the Oil Age*, pp. 89-124, 2021.

[4] E. E. Eweka, E. Lopez-Arroyo, C. O. Medupin, A. Oladipo and L. C. Campos, “Energy Landscape and Renewable Energy Resources in Nigeria,” A Review. *Energies*, *15*(15), pp. 5514, 2022.

[5] O. G. Igbum, A. C. Eloka-Eboka and S. Adoga, “Feasibility study of biogas energy generation from refuse dump in a community-based distribution in Nigeria,” *International Journal of Low-Carbon Technologies*, *14*(2), pp. 227-233, 2019.

[6] A.J. Adeleke, O.M. Ajunwa, J.A. Golden, U.E. Antia, A.T. Adesulu-Dahunsi, O.A. Adewara, O.D. Popoola, E.O. Oni, B.T. Thomas and Y. Luka, “Anaerobic Digestion Technology for Biogas Production: Current Situation in Nigeria (A Review),” *UMYU Journal of Microbiology Research (UJMR)*, *8*(2), pp.153-164, 2023.

[7] J. E. Agori, E. R. Iwemah, J. O. Etuke and L. O. Umukoro, “Utilization of digestate from anaerobic co-digestion of water hyacinth and poultry waste as a sustainable source of organic fertilizer,” *World Journal of Advanced Engineering Technology and Sciences*, *10*(2), pp. 074-081, 2023.

[8] Y. Sun, H. L. Dai, H. Moayedi, B. N. Le and R. M. Adnan, “Predicting steady-state biogas production from waste using advanced machine learning-metaheuristic approaches,” *Fuel*, *355*, pp. 129493, 2024.

[9] H. E. G. Akbay, “Anaerobic mono and co-digestion of agro-industrial waste and municipal sewage sludge: Biogas production potential, kinetic modelling, and digestate characteristics,” *Fuel*, *355*, 129468, 2024.

[10] O. B. Ezeudu, T. S. Ezeudu, U. C. Ugochukwu, J. C. Agunwamba and T. C. Oraelosi, “Enablers and barriers to implementation of circular economy in solid waste valorization: The case of urban markets in Anambra, Southeast Nigeria,” *Environmental and Sustainability Indicators*, *12*, pp.100150, 2021.

[11] I. O. Ogundari, “Techno-Economic Analysis of Waste-to-Suburban Cooking Energy Critical Infrastructure Development in Southwestern Nigeria,” *Journal of Energy and Power Technology*, *5*(2), pp.1-20, 2023.

[12] M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick and E. O. Oladipo, “Achieving Sustainable Development Goals in Nigeria’s power sector: assessment of transition pathways,” *Climate Policy*, *20*(7), pp. 846-865, 2020.

[13] X. Chai, D. J. Tonjes and D. Mahajan, "Methane emissions as energy reservoir: context, scope, causes and mitigation strategies," *Progress in Energy and Combustion Science*, *56*, pp. 33-70, 2016.

[14] A. Majdinasab and Q. Yuan, "Performance of the biotic systems for reducing methane emissions from landfill sites: A review," *Ecological Engineering*, *104*, pp. 116-130, 2017.

[15] C. Oya and N. Pontara, "*Rural Wage Employment in Developing Countries*," Taylor & Francis, 2015.

[16] K.E. Woolley, E. Dickinson-Craig, H.L. Lawson, J. Sheikh, R. Day, F.D. Pope, S.M. Greenfield, S.E. Bartington, D. Warburton, S. Manaseki-Holland and M.J. Price, "Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: A systematic review and meta-analysis," *Indoor air*, *32*(1), pp.12958, 2022.

[17] A. Mishra, M. Kumar, N. S. Bolan, A. Kapley, R. Kumar and L. Singh, "Multidimensional approaches of biogas production and up-gradation: opportunities and challenges," *Bioresource Technology*, *338*, pp. 125514, 2021.

[18] K. Hoffstadt, G.D. Pohen, M.D. Dicke, S. Paulsen, S. Krafft, J.W. Zang, W.A. da Fonseca-Zang, A. Leite and I. Kuperjans, "Challenges and prospects of biogas from energy cane as supplement to bioethanol production," *Agronomy*, *10*(6), pp.821, 2020.

[19] I. Jan, "Socio-economic characteristics influencing farmers' willingness-to-adopt domestic biogas technology in rural Pakistan," *Environmental Science and Pollution Research*, *28*(16), pp. 20690-20699, 2021.

[20] M. Herrero, B. Henderson, P. Havlík, P.K. Thornton, R.T. Conant, P. Smith, S. Wirsenius, A.N. Hristov, P. Gerber, M. Gill and K. Butterbach-Bahl, "Greenhouse gas mitigation potentials in the livestock sector," *Nature Climate Change*, *6*(5), pp.452-461, 2016.

[21] M. Harmsen, C. Tabak, L. Höglund-Isaksson, F. Humpenöder, P. Purohit and D. van Vuuren, "Uncertainty in non-CO2 greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility," *Nature Communications*, *14*(1), pp. 2949, 2023.

[22] M. Saleem, "Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source," *Heliyon*, *8*(2), 2022.

[23] H. Zhang, "*Release mechanisms of greenhouse gases, ammonia and hydrogen sulfide from liquid dairy manure"* (Doctoral dissertation, Purdue University), 2013.

[24] A. H. Abba, "Poultry house hydrogen sulphide emissions and impacts to neighbourhood environment in Yola, Nigeria," *Savannah Journal of Science and Engineering Technology*, *1*(4), pp. 231-236, 2023.

[25] A. Chini, C. E. Hollas, A. C. Bolsan, F. G. Antes, H. Treichel and A. Kunz, "Treatment of digestate from swine sludge continuous stirred tank reactor to reduce total carbon and total solids content," *Environment, Development and Sustainability*, *23*(8), pp. 12326-12341, 2021.

[26] M. Vítězová, A. Kohoutová, T. Vítěz, N. Hanišáková and I. Kushkevych, "Methanogenic microorganisms in industrial wastewater anaerobic treatment," *Processes*, *8*(12), pp. 1546, 2020.

[27] E. Valijanian, M. Tabatabaei, M. Aghbashlo, A. Sulaiman and Y. Chisti, "Biogas production systems," *Biogas: Fundamentals, process, and operation*, pp. 95-116, 2018.

[28] S. Y. Pan, C. Y. Tsai, C. W. Liu, S. W. Wang, H. Kim and C. Fan, "Anaerobic co-digestion of agricultural wastes toward circular bioeconomy," *Iscience*, *24*(7), 2021.

[29] M.R. Atelge, D. Krisa, G. Kumar, C. Eskicioglu, D.D. Nguyen, S.W. Chang, A.E. Atabani, A.H. Al-Muhtaseb and S. Unalan, "Biogas production from organic waste: recent progress and perspectives," *Waste and Biomass Valorization*, *11*, pp.1019-1040, 2020.

[30] R. Czubaszek, A. Wysocka-Czubaszek and P. Banaszuk, "Importance of Feedstock in a Small-Scale Agricultural Biogas Plant," *Energies*, *15*(20), pp. 7749, 2022.

[31] R. S. Bose, B. Chowdhury, B. S. Zakaria, M. K. Tiwari and B. R. Dhar, "Significance of different mixing conditions on performance and microbial communities in anaerobic digester amended with granular and powdered activated carbon," *Bioresource Technology*, *341*, pp.125768, 2021.

[32] Y. Cao, X. Wang, Z. Bai, D. Chadwick, T. Misselbrook, S.G. Sommer, W. Qin and L. Ma, "Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: a meta-analysis," *Journal of Cleaner Production*, *235*, pp.626-635, 2019.

[33] M. Szymańska, H. E. Ahrends, A. K. Srivastava and T. Sosulski, "Anaerobic Digestate from Biogas Plants—Nuisance Waste or Valuable Product?," *Applied Sciences*, *12*(8), pp. 4052, 2022.

[34] C. E. Okafor, A. C. Onovo, O. I. Ani, C. M. Obele, D. Dziki, C. C. Ihueze and C. U. Okonkwo, "Mathematical study of bio-fibre comminution process as first step towards valorization of post-harvest waste materials," *Cleaner Materials*, *4*, pp.100067, 2022a.

[35] T. Pandiselvi, R. Jeyajothiand and M. Kandeshwari, "Organic nutrient management a way to improve soil fertility and Sustainable Agriculture-A review," *International Journal of Advanced Life Sciences*, *10*(2), pp. 175-181, 2017.

[36] T. Bayu, "Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability," *Cogent Environmental Science*, *6*(1), pp. 1823631, 2020.

[37] C. E. Okafor, D. U. Okpe, O. I. Ani and U. C. Okonkwo, "Development of carbonized wood/silicon dioxide composite tailored for single-density shoe sole manufacturing," *Materials Today Communications*, *32*, pp.104184, 2022b.

[38] E. Ross, M. Day, C. Ivanova, A. McLeod and J. Lockshin, “Intersections of disadvantaged communities and renewable energy potential: Data set and analysis to inform equitable investment prioritization in the United States,” *Renewable Energy Focus*, *41*, pp. 1-14, 2022.

[39] A. Johari, H. Alkali, H. Hashim, S. I. Ahmed and R. Mat, “Municipal solid waste management and potential revenue from recycling in Malaysia,” *Modern Applied Science*, *8*(4), pp. 37, 2014.

[40] F. Bartolacci, R. Cerqueti, A. Paolini and M. Soverchia, “An economic efficiency indicator for assessing income opportunities in sustainable waste management,” *Environmental Impact Assessment Review*, *78*, pp. 106279, 2019.

[41] C. G. Tavera, T. Raab and L. H. Trujillo, “Valorization of biogas digestate as organic fertilizer for closing the loop on the economic viability to develop biogas projects in Colombia,” *Cleaner and Circular Bioeconomy*, *4*, pp. 100035, 2023.

[42] W. Zhao, H. Yang, S. He, Q. Zhao and L. Wei, “A review of biochar in anaerobic digestion to improve biogas production: Performances, mechanisms and economic assessments,” *Bioresource Technology*, *341*, pp. 125797, 2021.

[43] C.E. Okafor, I. Sunday, O.I. Ani, N. Akçakale, G.O. Ekwueme, P.C. Ugwu, E.C. Nwanna and A.C. Onovo, “Biobased hybrid composite design for optimum hardness and wear resistance,” *Composites Part C: Open Access*, *10*, pp.100338, 2023.

[44] B. Koo, “Examining the impacts of Feed-in-Tariff and the Clean Development Mechanism on Korea's renewable energy projects through comparative investment analysis,” *Energy Policy*, *104*, pp.144-154, 2017.

[45] P. Mukumba, G. Makaka, S. Mamphweli and P. M. Masukume, “Design, construction and mathematical modelling of the performance of a biogas digester for a family in the Eastern Cape province, South Africa,” *African Journal of Science, Technology, Innovation and Development*, *11*(3), pp. 391-398, 2019.

[46] W. J. Wardal, J. Barwicki, K. Mazur, M. Majchrzak and K. Borek, “Technical and economical aspects of biogas production from agricultural sources including Polish conditions,” *Agricultural Engineering*, *19*, 2015.

[47] M. J. Park, J. H. Kim, Y. H. Lee, H. M. Kim and D. W. Jeong, “System optimization for effective hydrogen production via anaerobic digestion and biogas steam reforming,” *International Journal of Hydrogen Energy*, *45*(55), pp. 30188-30200, 2020.

[48] I. Lanko, J. Hejnic, J. Říhová-Ambrožová, I. Ferrer and P. Jenicek, “Digested sludge quality in mesophilic, thermophilic and temperature-phased anaerobic digestion systems,” *Water*, *13*(20), pp. 2839, 2021.

[49] D. Nguyen, V. Gadhamshetty, S. Nitayavardhana and S. K. Khanal, “Automatic process control in anaerobic digestion technology: A critical review,” *Bioresource technology*, *193*, pp. 513-522, 2015.

[50] M. Safari, R. Abdi, M. Adl and J. Kafashan, “Optimization of biogas productivity in lab-scale by response surface methodology,” *Renewable Energy*, *118*, pp. 368-375, 2018.

[51] D.C. Montgomery, “Design and Analysis of Experiments,” John Wiley and Sons, New York, 2001.

[52] O. J. Odejobi, O. O. Ajala and F. N. Osuolale, “Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria,” *Biomass Conversion and Biorefinery*, *14*(2), pp.1567-1579, 2024.

[53] M. Wiśniewska, A. Kulig and K. Lelicińska-Serafin, “Odour nuisance at municipal waste biogas plants and the effect of feedstock modification on the circular economy—a review,” *Energies*, *14*(20), pp.6470, 2021.

[54] H. Yaqoob, Y. H. Teoh, Z. U. Din, N. U. Sabah, M. A. Jamil, M. A. Mujtaba and A. Abid, “The potential of sustainable biogas production from biomass waste for power generation in Pakistan,” *Journal of cleaner production*, *307*, pp.127250, 2021.

[55] A. D. Korberg, I. R. Skov and B. V. Mathiesen, “The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark,” *Energy*, *199*, pp.117426, 2020.

[55] U. J. Efetobor, A. O. Onokwai, E. Onokpite and U. C. Okonkwo, “Response surface methodology application for the optimization of biogas yield from an anaerobic Co-digestion process,” *environment*, *10*, pp.12, 2024.

[56] K. O. Olatunji, N. A. Ahmed, D. M. Madyira, A. O. Adebayo, O. Ogunkunle and O. Adeleke, “Performance evaluation of ANFIS and RSM modeling in predicting biogas and methane yields from Arachis hypogea shells pretreated with size reduction,” *Renewable Energy*, *189*, pp. 288-303, 2022.

[57] T. T.Olugasa, I. F. Odesola and M. O. Oyewola, “Energy production from biogas: A conceptual review for use in Nigeria,” *Renewable and Sustainable Energy Reviews*, *32*, pp.770-776,n 2014.

[58] T. R. Ayodele, A. S. O. Ogunjuyigbe and M. A. Alao, “Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria,” *Journal of cleaner production*, *203*, pp. 718-735, 2018.

[59] A. Roopnarain, B. Ndaba, M. Bello-Akinosho, E. Bamuza-Pemu, M. Mukhuba, R. Nkuna and R. Adeleke, “Biogas technology in Africa: an assessment of feedstock, barriers, socio-economic impact and the way forward,” *Biogas Production: From Anaerobic Digestion to a Sustainable Bioenergy Industry*, pp. 415-445, 2020.

[60] J. Pavičić, K. Novak Mavar, V. Brkić and K. Simon, “Biogas and biomethane production and usage:

technology development, advantages and challenges in Europe," *Energies*, *15*(8), pp. 2940, 2022.

[61] B. Steffen, V. Karplus and T. S. Schmidt, "State ownership and technology adoption: The case of electric utilities and renewable energy," *Research policy*, *51*(6), pp. 104534, 2022.

[62] J. P. Painuly and N. Wohlgemuth, "Renewable energy technologies: barriers and policy implications," In *Renewable-energy-driven future*, 2021, pp. 539-562, Academic Press.

[63] T. Nevzorova and E. Karakaya, "Explaining the drivers of technological innovation systems: The case of biogas technologies in mature markets," *Journal of Cleaner Production*, *259*, pp. 120819, 2020.

[64] S. A. Sarker, S. Wang, K. M. Adnan and M. N. Sattar, "Economic feasibility and determinants of biogas technology adoption: Evidence from Bangladesh," *Renewable and Sustainable Energy Reviews*, *123*, pp. 109766, 2020.

[65] W. G. Ding, Y. Wu and Q. Li, "Cost effectiveness analysis of household biogas plants in China," *Energy Sources, Part B: Economics, Planning, and Policy*, *8*(4), pp. 431-438, 2013.

[66] R. Bouyakhsass, S. Souabi, S. Bouaouda, A. Taleb, T. A. Kurniawan, X. Liang and A. Anouzla, "Adding value to unused landfill gas for renewable energy on-site at Oum Azza landfill (Morocco): Environmental feasibility and cost-effectiveness," *Trends in Food Science & Technology*, pp. 104168, 2023.

[67] P. Slavica, M. Ivica, R. Dragica, J. Milios, J. Slobodan and N. Vladislav, "Testing the energy efficiency of CHP engines and cost-effectiveness of biogas plant operation," *IET Renewable Power Generation*, *17*(3), pp. 555-562, 2023.

[68] O. I. Ani, G. N. Onoh, O. J. Akpor and C. A. Ukpai, "Design, development and performance evaluation of a mobile rice threshing machine," *International Journal of Emerging Trends in Engineering and Development*, (10), pp.7-17, 2020.

[69] S. Tundup, P. S. Roshini, A. Kumar, A. Sahoo and B. Paramasivan, "Evaluating the scientific contributions of biogas technology on rural development through scientometric analysis," *Environmental Technology & Innovation*, *24*, pp. 101879, 2021.

[70] M. Lisowyj and M. M. Wright, "A review of biogas and an assessment of its economic impact and future role as a renewable energy source," *Reviews in Chemical Engineering*, *36*(3), pp. 401-421, 2020.

[71] W. Guenther-Lübbers, H. Bergmann and L. Theuvsen, "Potential analysis of the biogas production–as measured by effects of added value and employment," *Journal of cleaner production*, *129*, pp. 556-564, 2016.

[72] R. Pringle, "*Moving towards whole settlement energy self-sufficiency in rural communities* (Doctoral dissertation, Newcastle University)," 2015.

[73] A. M. Esteves, A. Genus, T. Henfrey, G. Penha-Lopes and M. East, "Sustainable entrepreneurship and the Sustainable Development Goals: Community-led initiatives, the social solidarity economy and commons ecologies," *Business Strategy and the Environment*, *30*(3), pp. 1423-1435, 2021.

[74] J. F. Akinbami, M. O. Ilori, T. O. Oyebisi, I. O. Akinwumi and O. Adeoti, "Biogas energy use in Nigeria: current status, future prospects and policy implications," *Renewable and Sustainable Energy Reviews*, *5*(1), pp. 97-112, 2001.

[75] M. K. Ibro, V. R. Ancha and D. B. Lemma, "Impacts of anaerobic co-digestion on different influencing parameters: a critical review," *Sustainability*, *14*(15), pp. 9387, 2022.

[76] C. Li, J. E. Aston, J. A. Lacey, V. S. Thompson and D. N. Thompson, "Impact of feedstock quality and variation on biochemical and thermochemical conversion," *Renewable and Sustainable Energy Reviews*, *65*, pp. 525-536, 2016.

[78] S. Singh and J. Ru, "Accessibility, affordability, and efficiency of clean energy: a review and research agenda," *Environmental Science and Pollution Research*, *29*(13), pp. 18333-18347, 2022.

[79] B. F. Giannetti, F. J. D. Lopez, G. Liu, F. Agostinho, F. Sevegnani and C. M. Almeida, "A resilient and sustainable world: Contributions from cleaner production, circular economy, eco-innovation, responsible consumption, and cleaner waste systems," *Journal of cleaner production*, *384*, pp. 135465, 2023.

[80] V. Ranta and U. A. Saari, "Circular economy: enabling the transition towards sustainable consumption and production," *Responsible consumption and production*, pp. 78-89, 2020.