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Biogas as renewable energy source: A brief overview

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ABSTRACT

Biogas has emerged as a versatile and sustainable energy source, offering a wide range of environmental, economic, and social benefits. It plays a critical role in addressing pressing global challenges such as waste management, greenhouse gas reduction, and energy security. The development and widespread adoption of biogas technologies are integral to the transition towards a low-carbon, circular economy. Environmental sustainability is a central objective in the ongoing evolution of biogas systems, ensuring that their impact on both the environment and society is positive and enduring. Continued advancements in biogas production technologies, combined with strategic investments in research and development, are essential for enhancing the efficiency and scalability of biogas systems. By addressing existing challenges and promoting innovation, biogas has the potential to become a key component of the global shift towards a more sustainable energy framework. This article reviews the key achievements and challenges in the development of biogas technologies, highlighting a selection of technological solutions, evaluating their advantages and limitations, and discussing their potential applications.

Keywords: biogas, RES, developments and challenges, innovative technologies, environmental benefits, recommendations and perspectives.

INTRODUCTION

Biogas, generated from organic matter through anaerobic digestion (AD), is gaining prominence as a renewable energy source worldwide. The AD is a biochemical process in which microorganisms decompose organic matter in the absence of oxygen, generating energy and by-products such as biogas (primarily methane and carbon dioxide). It consists of four main stages: (i) hydrolysis – complex organic compounds are broken down into simpler molecules such as amino acids, fatty acids, and sugars, (ii) acidogenesis – fermentative bacteria convert these molecules into organic acids, alcohols, hydrogen, and carbon dioxide, (iii) acetogenesis – organic acids and alcohols are further transformed into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria and (iv) methanogenesis – methanogenic archaea convert acetic acid, hydrogen, and carbon dioxide into methane and additional carbon dioxide, completing the process (Piadeh et al., 2024). Depending on the fermentation conditions and the chemical composition of the substrates, up to 500 mL of biogas can be obtained from one gram of organic matter. The main components of biogas are methane (40–80%), carbon dioxide (20–55%), hydrogen sulphide (0.1–5.5%), as well as hydrogen, carbon monoxide, nitrogen, and oxygen in trace amounts. Recent developments highlight its potential in reducing greenhouse gas emissions and contributing to sustainable energy transitions. In Europe, biogas plays a crucial role in achieving climate objectives. For instance, the importance of renewable gases in decarbonisation efforts has been consistently emphasised (Gulnar et al., 2024). In the United States, the biogas sector is also experiencing dynamic growth. The American Biogas Council reported a 21% increase in farm-based digesters in 2021, reflecting a rising interest in converting agricultural waste into energy (US EPA, OAR, 2016).

The development of biogas technologies as a renewable energy source (RES) offers numerous environmental and economic benefits. Chief among these is the efficient management of organic waste, including food scraps, agricultural residues, and sewage sludge, which are converted into usable energy (Pilarska et al., 2023). This process contributes to the reduction of greenhouse gas emissions, particularly methane, which would otherwise be released into the atmosphere through uncontrolled decomposition of organic matter. Additionally, biogas can be utilised as an eco-friendly fuel for electricity and heat generation, as well as for transport, supporting energy diversification and reducing dependence on fossil fuels. Notably, the digestate produced as a by-product can serve as a natural fertiliser, enhancing sustainable agricultural practices. The expansion of this sector also stimulates local economies by creating jobs and promoting sustainable practices, particularly in rural areas. Biogas plants, with their potential for decentralisation, enable energy production close to raw material sources, fostering community development (Igliński et al., 2023, Pilarski et al., 2023). Furthermore, biogas aligns with circular economy goals by minimising waste and supporting sustainable resource management. In the long term, biogas can significantly enhance energy security by reducing reliance on volatile fossil fuel markets.

Despite these advancements, challenges persist. Environmental groups highlight the need for stringent regulatory frameworks to address methane leakage and emissions during production. Economic scalability also remains a concern, particularly for small-scale biogas systems. The high initial investment costs and long payback periods can deter potential investors, limiting the expansion of biogas projects. Additionally, the variability in feedstock availability and quality affects the efficiency and consistency of biogas production. Further research into advanced digestion techniques and process optimisation is necessary to enhance system efficiency and reliability. Continued innovation and supportive policies will be crucial in overcoming these challenges and fully realising the potential of biogas as a renewable energy solution (Alayi et al., 2016; Sher et al., 2024).

The aims of this paper is to present the key achievements and challenges in the field of biogas development and to introduce AD technology with a characterisation of selected advanced solutions and an indication of the criteria for selecting the appropriate technology.

BIOGAS technologies

Biogas production is an evolving field, with cutting-edge research addressing existing challenges and uncovering novel applications. Recent scientific advancements have considerably enhanced biogas production, solidifying its role as a renewable energy source. Key innovations in reactor design, feedstock pre-treatment technologies, and microbial engineering have notably improved production efficiency and yield. Emerging technologies, such as AI-driven optimisation systems and Power-to-X integration, are transforming biogas plants into hubs of technological innovation.

One promising advancement is autogenerative high-pressure digestion (AHPD), which utilises naturally occurring microbial activity to generate elevated pressures within the reactor (Lindeboom et al., 2011). This process increases methane concentration in the biogas, reducing the need for extensive post-production upgrading. Pre-treatment technologies have also played a critical role in improving biogas yields. Chemical, physical, thermochemical, and oxidative pre-treatments enhance the breakdown of complex organic materials, rendering them more accessible for microbial digestion and boosting biomethane production. These improvements contribute to the development of more efficient biogas systems (Witaszek et al., 2020; Sher et al., 2024).

Furthermore, the integration of deep learning and artificial intelligence (AI) has optimised biogas production processes. Mahmoodi-Eshkaftaki et al. (2022) developed a deep learning neural network model to dynamically optimise volatile fatty acids during anaerobic digestion, which resulted in improved biohydrogen yields, highlighting the potential of AI to enhance biogas production efficiency. Real-time monitoring and optimisation, powered by Internet of Things (IoT) devices and AI algorithms, are becoming standard in biogas facilities. The deployment of sensors and predictive models allows operators to maintain optimal conditions for anaerobic digestion, ensuring consistent and efficient biogas output (Chinh et al., 2021). Additionally, integrating biogas plants with Power-to-X systems for hydrogen and e-methanol production is being explored. This integration could enhance energy storage solutions, contributing to a more resilient renewable energy infrastructure (Alamia et al., 2024).

A notable development is the use of multi-feedstock approaches. By combining agricultural residues, food waste, and municipal solid waste, researchers have achieved higher biogas yields. This synergy arises from the complementary properties of mixed feedstocks, providing a more balanced nutrient profile for microbial digestion (Su et al., 2022). Furthermore, advancements in microbial engineering are revolutionising the anaerobic digestion process. Genetically modified microbes are being incorporated to enhance the breakdown of recalcitrant organic materials, thus improving biogas production efficiency (Pandya et a., 2024). The integration of biogas plants with carbon capture and storage (CCS) technology also presents an exciting opportunity to achieve carbon-negative energy solutions. Such developments position biogas as a leader in global renewable energy transitions (Selim et al., 2024). This integration aligns with international net-zero targets and positions biogas as a vital player in combating climate change.

Dry fermentation and wet fermentation

Dry fermentation and wet fermentation are two distinct approaches in the AD process, differentiated primarily by the water content of the feedstock. Dry fermentation involves substrates with low moisture content, typically below 30%, resulting in a more concentrated feedstock that reduces space requirements in the digester. This configuration is particularly beneficial in situations where space constraints are a significant factor, such as small-scale biogas plants (Rocamora et al., 2020). Additionally, dry fermentation allows for lower transportation costs due to the reduced volume of water that needs to be managed. However, the main challenges of dry fermentation include difficulties in mixing the feedstock, which can lead to uneven microbial distribution and higher risks of sedimentation (Hayyat et al., 2024).

In contrast, wet fermentation processes utilise substrates with higher water content, typically ranging between 70% and 90%, making it easier to transport and mix the materials in the digester. The higher water content facilitates better interaction between the feedstock and the microorganisms responsible for degradation, enhancing process stability and efficiency (Czubaszek et al., 2021; Cassimiro et al., 2023). However, wet fermentation requires more space and significantly increases transportation costs due to the higher water volume. Furthermore, managing the large quantities of water involved in the process presents additional operational challenges, such as the need for water treatment and disposal (Wu et al., 2023). Despite these challenges, wet fermentation is often preferred in larger-scale biogas plants due to its operational stability and better uniformity during the fermentation process. Figure 1 presents an example of a biogas plant constructed using NaWaRo (German technology) in 2014.

The NaWaRo technology, in which this facility was built, is the most widely used biogas plant construction technology in Europe. Over 90% of all installations are built using this technology or its derivatives.

Biogas plants operating with this technology are primarily fuelled by plant-based substrates (such as silage, fruit and vegetable pomace, or distillery residues) as well as liquid manure. However, this technology presents several technical challenges, particularly related to inefficient

Figure 1. A biogas plant using NaWaRo technology; a facility from 2014

mixing, which often leads to the formation of surface crusts and bottom sediments. Consequently, fermentation tanks require cleaning every 4–8 years to remove accumulated deposits. From a technical perspective, replacing the agitators also poses significant difficulties, as it necessitates halting the process, removing the fermenter dome, and emptying the tank.

Single-stage and multi-stage fermentation systems

The configuration of fermentation systems, whether single-stage or multi-stage, plays a crucial role in determining the efficiency and control over the anaerobic digestion process. Single-stage fermentation systems are characterised by the simultaneous occurrence of all fermentation phases in a single digester. This configuration simplifies the process and reduces the initial capital investment, making it particularly suitable for small- and medium-sized biogas plants (Schievano et al., 2012). The simplicity of single-stage systems, however, comes at the cost of reduced process control, as all stages of fermentation occur under the same conditions, limiting the ability to optimise the process at various stages. As a result, the overall efficiency of the system is generally lower compared to multi-stage configurations (Du et al., 2017).

Multi-stage fermentation systems, on the other hand, divide the process into distinct stages, typically including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This approach allows for better control over each phase, with specific conditions tailored to optimise microbial activity in each stage (Rabii et al., 2019). For example, hydrolysis may be optimised at lower temperatures, while methanogenesis is more efficient at higher temperatures. The ability to manage each stage separately results in improved overall efficiency and stability, particularly when dealing with complex or varied feedstocks. However, multi-stage systems require more advanced infrastructure, higher capital costs, and more complex management strategies, which may be prohibitive for smaller-scale applications. Nonetheless, their higher efficiency and the potential for process optimisation make them an attractive option for large-scale biogas production.

An example of a biogas plant where the process operates with phase separation is the facility constructed using Dynamic Biogas (Polish technology), commissioned in 2019 (see Figure 2). This plant is located at the Agricultural and Horticultural Experimental Farm in Przybroda, which is part of the Poznań University of Life Sciences (Janczak and Mazurkiewicz, 2019).

The Dynamic Biogas technology is characterised by the separation of fermentation phases, incorporating a hydrolyser – also referred to as a biotechnological accelerator – for conducting hydrolysis and acidogenesis at a low pH. Additionally, the fermentation tanks are constructed from acid-resistant steel and have a diameter smaller than the height of the fermenters.

The fermenters are equipped with a vertical mixing system, consisting of a tubular vertical propeller with a motor and impeller inside. This design effectively eliminates the risk of surface crust formation and bottom sediment accumulation. Furthermore, this mixing system facilitates agitator maintenance, as the motor and impeller can be replaced in less than an hour without interrupting the fermentation process.

Figure 2. A biogas plant using dynamic biogas technology; a facility from 2019 located in Przybroda

Thermophilic and mesophilic fermentation

The temperature regime during anaerobic digestion significantly impacts the rate of biogas production, microbial community dynamics, and the overall efficiency of the process. Thermophilic fermentation, which operates at temperatures between 50 °C and 60 °C, is characterised by faster degradation of organic matter and higher biogas production rates (Ryue et al., 2020). This temperature regime is particularly advantageous for processing large quantities of feedstock within a shorter timeframe, making it suitable for large-scale biogas plants. Furthermore, the elevated temperatures in thermophilic processes contribute to better pathogen reduction and more efficient disinfection of the feedstock. However, thermophilic systems require more precise temperature control, higher energy inputs, and are more susceptible to process destabilisation, especially when subjected to fluctuations in feedstock composition or other operational variables.

Mesophilic fermentation, operating at temperatures between 30 °C and 40 °C, is the most widely used and stable anaerobic digestion process (Pilarska et al., 2022). It is less sensitive to temperature fluctuations, requires less energy for heating, and tends to be more resilient, especially when processing organic waste with varying compositions. While mesophilic fermentation is slower compared to thermophilic digestion, it remains the preferred choice for most biogas plants due to its operational stability and lower energy requirements (Alrowais et al., 2023; Ibro et al., 2024). Nonetheless, mesophilic systems typically result in lower biogas yields per unit of feedstock, as the process is slower and less efficient in breaking down complex organic materials.

Advanced biogas technologies

In addition to the fundamental fermentation configurations, advanced technologies are continuously being integrated into the anaerobic digestion process to improve its efficiency and sustainability. One of the primary advancements involves the comparison between continuous and batch systems. Continuous systems are designed for the steady addition of feedstock and removal of digestate, providing a stable and uninterrupted process. These systems ensure consistent operation and are ideal for large-scale plants where continuous feedstock availability is a given (Obiukwu and Nwafor, 2014). In contrast, batch systems operate in cycles, adding feedstock, running the fermentation process, and then removing the digestate in discrete intervals. While batch systems offer greater flexibility and can be more adaptable to varying feedstock characteristics, they demand more precise management to ensure the process remains stable and efficient (Thuan et al., 2023).

Furthermore, technologies involving enzyme and microorganism additives are increasingly utilised to optimise the fermentation process. The addition of specific enzymes can accelerate the breakdown of complex organic compounds, improving the overall rate of digestion. Similarly, incorporating specialised microorganisms into the fermentation process can enhance the degradation of certain substrates, thereby increasing the efficiency and methane yield of the system (Pilarska et al., 2024). These innovations help overcome the limitations of standard fermentation processes, making the system more efficient and capable of handling more complex or difficult-to-digest organic materials.

Additionally, modern biogas plants are incorporating advanced technologies for mixing, aeration, and automation, which provide real-time data and control over the fermentation process. These innovations allow for more efficient management of the anaerobic digestion process, improving both its stability and output (Devi et al., 2022; Sher et al., 2024). Advanced sensors and monitoring systems enable operators to track key variables such as temperature, pH, and biogas production rates, adjusting the process as necessary to optimise performance. Automation systems reduce the need for human intervention, ensuring a more consistent and reliable fermentation process.

A good example of advanced technology is the Polish ProBioGas technology, which is more extensively described in the report of Biomass magazine (Report Biogas in Poland, 2020), see Figure 3. The biogas plant using ProBioGas technology is a very specific technology in which fermentation takes place in a long (up to 75 m) reactor, often referred to as “intestinal” fermentation. The fermenting pulp moves linearly, gradually changing its physical and chemical parameters. This technology also involves the separation of fermentation phases. A separate chamber for preliminary mixing, which initiates the hydrolysis stage, is distinguished, followed by an acid-hydrogen chamber with an intensive phase of so-called acidic hydrolysis (where hydrolysis and

Figure 3. A biogas plant using ProBioGas technology located in Międzyrzecz Podlaski

acidogenesis occur). Acetogenesis and methanogenesis, in turn, take place in the long chambers of the main fermentation. This solution enables the efficient change of substrates fed to the fermenter and is characterised by an exceptionally high degree of biomass fermentation (98%). ProBioGas technology also allows for the production of biohydrogen in the acid-hydrogen chamber. The installation shown in the photo (Figure 3), which was the first in the world, produced more than 2000 Nm³/day of biohydrogen in the spring of 2013 as a result of the dark fermentation process.

Selection of appropriate technology

The choice of the most suitable fermentation technology depends on several critical factors. These include the type and availability of feedstock, as different feedstocks may require specific configurations to maximise biogas production. For instance, complex organic waste materials may benefit from multi-stage or thermophilic fermentation systems, which can more effectively degrade these materials. The scale of production is another crucial consideration; larger-scale operations typically favour continuous systems and multi-stage processes due to their ability to handle higher volumes of feedstock more efficiently (Ali et al., 2023).

Operational requirements such as temperature control, system complexity, and ease of management must also be factored into the decision-making process. Smaller-scale operations may benefit from single-stage systems or batch fermentation due to lower initial costs and simpler management. On the other hand, larger biogas plants may require more advanced configurations, such as multi-stage systems and thermophilic fermentation, to optimise productivity and ensure operational stability.

Finally, the economic aspect, including both capital and operational costs, plays a significant role in determining the appropriate technology. The initial capital investment required for advanced systems like multi-stage or thermophilic processes can be high, but these technologies often result in higher biogas yields and more efficient operation in the long run. Conversely, simpler systems like single-stage or mesophilic processes may have lower upfront costs but could result in higher operational expenses due to lower efficiency.

CHALLENGES AND INNOVATIONS

Despite significant advancements in biogas production, several challenges and knowledge gaps continue to hinder its widespread adoption and optimisation. Key obstacles include feedstock variability, microbial community dynamics, economic feasibility, environmental sustainability, and policy inconsistencies. Effectively addressing these challenges requires a multidisciplinary approach that integrates technological advancements, regulatory improvements, and socio-economic considerations.

A primary challenge is the variability in feedstock composition, availability, and contamination levels. Organic materials such as agricultural residues, food waste, and sewage sludge exhibit diverse characteristics that directly impact biogas yield and process stability. Research into optimised feedstock blends and scalable pretreatment technologies is essential to ensuring a consistent and efficient feedstock supply. Additionally, developing robust strategies to manage seasonal fluctuations and contamination will be critical for improving process reliability and overall efficiency (Hayyat et al., 2024, Igliński et al., 2023). Enhancing microbial processes is another crucial area of focus. The anaerobic digestion process depends on complex microbial communities, yet the effects of environmental factors – such as pH, temperature, and nutrient balance – on microbial dynamics remain insufficiently understood. Advancing microbial engineering techniques to develop resilient and high-performing microbial consortia could improve process stability and efficiency, even under fluctuating feedstock conditions.

Economic feasibility remains a significant barrier, particularly for small-scale biogas systems in rural areas. High initial investment and operational costs often render projects financially unviable without subsidies or innovative financing mechanisms. Research suggests that government incentives, improved regulatory frameworks, and decentralised modular biogas systems could help reduce costs and attract investment, making biogas technology more accessible to smaller communities (Janczak and Mazurkiewicz, 2019).

Technological innovation is essential to advancing biogas production. Improving reactor designs, refining operational strategies, and integrating advanced monitoring technologies – such as sensors and artificial intelligence-driven optimisation – can enhance efficiency, scalability, and reliability. One of the significant challenges in biogas plants is the efficient mixing of the substrate. Selecting the appropriate mixers is critical to ensure uniformity and prevent the formation of scum, which can hinder the process and increase operational costs. Moreover, integrating biogas with other renewable energy sources, such as solar and wind, could facilitate energy storage and grid stability. Converting biogas into alternative energy carriers, such as hydrogen or synthetic fuels, further expands its applications and strengthens its role in future energy systems.

Environmental sustainability must remain a priority. Methane leakage during production, storage, and distribution can significantly undermine the environmental benefits of biogas, while improper digestate management – the by-product of anaerobic digestion – poses risks to soil and water quality. Strategies to mitigate emissions, including advanced reactor designs and stricter regulatory frameworks, are actively being explored. Additionally, innovative applications for digestate, such as biofertilisers and industrial materials, could contribute to a circular economy and reduce environmental impact (Pradeshwaran et al., 2024).

Policy inconsistencies and limited public awareness further impede the adoption of biogas technology. Misconceptions regarding its scalability and environmental impact hinder public acceptance, while fragmented policies across different jurisdictions create obstacles to the development of a standardised regulatory framework. A coordinated effort among researchers, policymakers, and industry stakeholders is necessary to establish clear, supportive policies that facilitate the integration of biogas into national and international energy systems (Pradeshwaran et al., 2024).

A comprehensive and systematic approach to these challenges is essential to unlocking the full potential of biogas technology. Through targeted research, technological advancements, and regulatory improvements, biogas can be established as a key component of the global renewable energy transition, contributing to long-term sustainability, energy security, and environmental protection.

CONCLUSIONS

Biogas technology represents a crucial element of the transition towards sustainable energy systems. Its ability to convert organic waste into a renewable energy source offers significant environmental, economic, and social benefits. Advancements in reactor design, feedstock pretreatment, microbial engineering, and AI-driven process optimization have improved biogas efficiency and yield, further solidifying its role in renewable energy transitions. Despite these achievements, several challenges persist, including feedstock variability, methane leakage, high initial costs, and policy inconsistencies. Addressing these challenges requires continued research, investment in innovative technologies, and supportive regulatory frameworks. The integration of biogas with emerging technologies such as Power-to-X and carbon capture and storage presents additional opportunities to enhance its impact. With ongoing advancements and strategic policy support, biogas has the potential to become a cornerstone of sustainable energy production, contributing significantly to global climate objectives and energy security.

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