

Technical, Economic, Social, and Environmental Dimensions in Biogas Energy Development

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ABSTRACT

Biogas energy has emerged as a sustainable, renewable energy source that can help tackle global issues like energy security, climate change, waste management, and the development of a circular economy. It is produced through the anaerobic digestion of organic materials such as agricultural leftovers, livestock manure, municipal solid waste, food waste, and wastewater sludge. Biogas presents significant opportunities to reduce greenhouse gas emissions while generating renewable electricity, heat, and biomethane. Despite gaining more attention from researchers, the existing studies are often fragmented. They usually focus on individual technical, economic, environmental, or social aspects without properly looking at how these areas are connected. This study carries aims to bring together current knowledge on biogas energy development and to clarify the factors that influence its successful implementation. The study integrates peer-reviewed studies published from 2015 to 2026, gathered from major scholarly peer-reviewed journal articles. The selected literature is analyzed using a structured systematic review method to pinpoint key research themes, drivers for implementation, technological innovations, barriers, and outcomes related to sustainability in biogas energy systems. The findings categorize the main factors affecting biogas development into five major areas: availability of feedstock, anaerobic digestion technology, recovery and use of resources, policy and financial support, and applications of end-use energy. Additionally, the review assesses the numerous benefits and barriers from technical, economic, environmental, and social viewpoints, emphasizing their connected relationships within sustainable energy systems. The study adds to the growing literature on renewable energy by putting forward a combined conceptual framework that illustrates the interactions among these four sustainability dimensions in biogas energy development. The framework shows how technological improvements boost environmental performance, economic feasibility, and social acceptance while also recognizing the challenges tied to investment costs, operational complexity, policy uncertainty, and engagement with stakeholders. Lastly, the review points out new research directions and offers practical advice for policymakers, researchers, industry professionals, and investors who want to speed up the adoption of biogas technologies and aid the global shift toward a low-carbon circular economy.

Keywords: Circular economy; Biogas energy; Anaerobic digestion; Renewable energy; Circular economy; Sustainability

INTRODUCTION

The rising global demand for clean, affordable, and sustainable energy has sped up the shift from fossil fuel-based systems to renewable energy technologies. Growing greenhouse gas (GHG) emissions, climate change, population increases, rapid urban growth, and industrial expansion have heightened concerns about energy security and environmental sustainability. As a result, renewable energy has become a key focus for governments, industries, and international organizations aiming to achieve sustainable development while lowering reliance on traditional fossil fuels. Among various renewable energy options, biogas stands out as a promising alternative because it effectively tackles waste management, renewable energy production, GHG

reduction, and resource recovery within the framework of a circular economy (Scarlat et al., 2018; Al Seadi et al., 2018; Lapiso & Roubík, 2025).

Biogas is created through the anaerobic digestion of biodegradable materials, including livestock manure, agricultural byproducts, food waste, municipal solid waste, sewage sludge, and industrial organic waste. In the anaerobic digestion process, microorganisms break down organic matter without oxygen, generating a combustible gas primarily made up of methane (CH₄) and carbon dioxide (CO₂), along with small amounts of hydrogen sulfide, ammonia, and water vapor. The resulting biogas can be used for generating electricity, producing heat, powering combined heat and power (CHP) systems, serving as cooking fuel, providing transportation fuel after upgrading to biomethane, or being injected into existing natural gas networks. The anaerobic digestion process also produces nutrient-rich digestate, which can be used as organic fertilizer, helping recover valuable nutrients and decreasing reliance on synthetic fertilizers (Mao et al., 2015; Monlau et al., 2021; Alipoursarbani et al., 2026).

The significance of biogas goes beyond renewable energy production. Biogas technology directly contributes to numerous United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). By turning biodegradable waste into renewable energy, biogas systems cut methane emissions from uncontrolled waste breakdown, reduce landfill use, improve sanitation, recover nutrients, and encourage sustainable waste management practices. Consequently, biogas has become a vital part of circular economy strategies that aim to maximize resource efficiency while minimizing environmental damage (Behzadian et al., 2023; Lapiso & Roubík, 2025).

Recent years have seen significant growth in biogas research due to increasing global commitments to carbon neutrality, renewable energy diversification, and sustainable waste management. Previous studies have explored various aspects of biogas systems, including optimizing feedstock, anaerobic digestion technologies, microbial community dynamics, co-digestion processes, biomethane upgrading, life cycle assessment (LCA), techno-economic analysis, environmental performance, and policy evaluations. Several review articles have also examined digestate management, resource recovery, GHG reduction, and sustainability assessments. While these studies have improved scientific understanding, they often focus on individual technical, economic, environmental, or policy issues without adequately addressing the complex interconnections among the multiple sustainability aspects that affect the successful implementation of biogas systems (Mannina et al., 2021; Behzadian et al., 2023).

Implementing biogas technologies involves several connected challenges that go beyond engineering performance. Technical hurdles include feedstock diversity, process instability, methane yield optimization, digester design, operational efficiency, and biogas upgrading technologies. Economic challenges stem from high capital investments, operational and maintenance expenses, unpredictable financial returns, limited access to funding, and fluctuating energy prices. Environmental issues involve GHG emissions, digestate use, nutrient recovery, land-use impacts, and overall environmental performance. Social factors also play a crucial role; public awareness, stakeholder acceptance, institutional capacity, regulatory support, and community involvement significantly affect technology adoption and long-term sustainability. These various factors interact during the planning, implementation, operation, and commercialization phases of biogas projects, making integrated evaluation essential for sustainable development (Mao et al., 2015; Behzadian et al., 2023).

Several countries have successfully shown the potential of biogas technology in different socio-economic settings. Germany has built one of the largest agricultural biogas industries worldwide, thanks to supportive renewable energy policies and feed-in tariffs. China and India have launched extensive household and community biogas programs to enhance rural energy access while reducing reliance on traditional biomass fuels. Denmark has successfully plugged agricultural biogas into its national energy system through coordinated policies, cooperative ownership structures, and advanced biomethane upgrading technologies. These global examples highlight that technological innovation, effective regulations, financial incentives, and stakeholder cooperation are vital to successful biogas development (Scarlat et al., 2018; Lapiso & Roubík, 2025).

Despite these advancements, significant knowledge gaps persist regarding the integration of technical, economic, environmental, and social aspects in biogas energy systems. Current literature remains scattered across engineering, environmental science, agricultural economics, energy policy, and sustainability fields, which limits a full understanding of how these areas together influence project success. Moreover, rapid technological advancements, shifting renewable energy policies, increasing carbon reduction commitments, and expanding circular economy initiatives require an updated overview of existing knowledge. Therefore, a systematic literature review (SLR) is necessary to gather existing evidence, identify emerging research trends, assess implementation barriers and sustainability advantages, and create a thorough conceptual framework for future research and policy development (Mannina et al., 2021; Lapiso & Roubík, 2025).

This study aims to compile the existing knowledge on biogas energy development via a systematic literature review. Specifically, the review addresses two research questions:

1. What are the key factors influencing the development and implementation of biogas energy systems in different sectors and regions?
2. How do the technical, economic, environmental, and social aspects interact to affect the sustainability, performance, and long-term acceptance of biogas energy technologies?

To answer these questions, this study follows the systematic literature review framework suggested by Snyder (2019). This framework offers a clear and reproducible method for synthesizing peer-reviewed evidence. The review highlights the main drivers, barriers, opportunities, and sustainability outcomes linked to biogas energy while examining their interactions across the four key sustainability areas. Based on the findings, an integrated conceptual framework is proposed to illustrate how technical innovation, economic viability, environmental sustainability, and social acceptance work together to influence the successful development of biogas energy systems. This framework contributes to renewable energy literature by providing a comprehensive view that aids future research, policy-making, and strategic decision-making for sustainable energy transitions.

Sustainability and Biogas Energy

Sustainability has become a key principle in global energy policy as countries strive to balance economic growth, environmental protection, and social welfare. Growing worries about climate change, fossil fuel depletion, and rising energy demand have sped up the shift toward renewable energy systems that support long-term environmental and economic stability. In this context, biogas energy has emerged as a vital part of sustainable energy systems. It addresses renewable energy production, waste management, greenhouse gas (GHG) reduction, and resource recovery through circular economy principles (Scarlat et al., 2018; Alengebawy et al., 2024). Anaerobic digestion turns biodegradable organic materials—including livestock manure, agricultural byproducts, food waste, municipal solid waste, and wastewater sludge—into biogas. This biogas can be used for generating electricity, heating, cooking, or upgraded to biomethane for transportation or injection into the natural gas grid. Additionally, the process produces digestate that can be used as organic fertilizer, allowing for nutrient recovery and decreasing reliance on chemical fertilizers. These multiple outputs show that biogas systems aid in sustainable resource use while reducing environmental pollution.

The idea of sustainable development, introduced by the World Commission on Environment and Development (WCED, 1987), highlights the need to meet present needs without jeopardizing future generations' ability to meet their own needs. This idea is usually implemented through three pillars of sustainability: environmental protection, economic viability, and social equity (Elkington, 1997). Biogas energy is closely connected to these areas. It provides renewable energy, tackles waste disposal issues, creates jobs, improves rural living conditions, and supports local economic growth. Unlike conventional fossil fuels, biogas is derived from renewable biomass resources that continually regenerate through agriculture, livestock farming, food processing, and municipal waste. Thus, biogas fosters renewable energy security and sustainable waste management while lowering reliance on non-renewable energy sources (Abanades et al., 2022; Shah et al., 2024).

One of the strongest contributions of biogas to sustainability is its role in supporting the circular economy. The circular economy encourages efficient resource use by reducing waste and promoting the reuse, recycling, and recovery of materials throughout their life cycles. Instead of viewing organic waste as a burden, anaerobic digestion turns waste into valuable products, including renewable energy and nutrient-rich digestate. This method not only diverts biodegradable waste from landfills but also reintroduces organic matter into agricultural soils, closing nutrient loops. As a result, biogas systems embody the waste-to-resource philosophy central to circular economy strategies and enhance resource efficiency in agricultural, industrial, and municipal sectors.

Environmental sustainability is one of the strongest reasons for expanding biogas production. Organic waste in landfills decomposes without oxygen, releasing methane, a greenhouse gas that is much more potent than carbon dioxide over a 100-year period. Capturing methane through controlled anaerobic digestion and using it as renewable energy significantly cuts greenhouse gas emissions and reduces fossil fuel use. Moreover, using digestate boosts soil fertility, increases soil organic carbon, and lessens the need for synthetic fertilizers, therefore lowering emissions linked to fertilizer production and use. Recent life-cycle assessment studies show that well-managed biogas systems can lead to significant reductions in carbon emissions and provide additional environmental advantages such as odor control, pathogen reduction, and better waste sanitation.

From an economic standpoint, biogas supports sustainable development by diversifying energy supplies, lowering energy import reliance, and creating new value chains from agricultural and municipal waste. Farmers and agro-industries can earn extra income by turning livestock manure and crop waste into energy, while municipalities can cut waste management costs with anaerobic digestion facilities. The commercialization of biomethane, renewable electricity, and digestate further improves the financial viability of biogas projects. However, the economic sustainability of biogas systems relies on several factors, including the availability of feedstock, plant size, investment costs, operational efficiency, government incentives, energy prices, and carbon markets. High initial investment and operational costs are major challenges, especially in developing countries where access to financing and technical knowledge is limited.

Social sustainability is also crucial for the successful rollout of biogas technologies. Biogas systems improve public health by reducing uncontrolled waste disposal, cutting odors, and lowering indoor air pollution caused by traditional biomass fuels. In rural areas, household and community-scale digesters ensure reliable access to clean cooking fuel and electricity, reducing reliance on firewood and raising living standards. Furthermore, biogas projects create job opportunities in feedstock collection, plant construction, operation, maintenance, and agricultural services. Despite these benefits, public acceptance, institutional capacity, stakeholder engagement, and policy support are important for the successful adoption of biogas. Raising community awareness, providing technical training, and having supportive governance are essential for ensuring the long-term sustainability of biogas development.

Biogas's contribution to global sustainability aligns with the United Nations Sustainable Development Goals (SDGs). It helps achieve SDG 7 (Affordable and Clean Energy) through renewable energy generation, supports SDG 11 (Sustainable Cities and Communities) by enhancing municipal waste management, backs SDG 12 (Responsible Consumption and Production) through resource recovery and circular economy practices, aids in SDG 13 (Climate Action) by reducing greenhouse gas emissions, and promotes SDG 15 (Life on Land) through nutrient recycling and sustainable agricultural methods. As countries work toward carbon neutrality and net-zero emission goals, biogas is increasingly seen as a crucial element of integrated renewable energy strategies, especially when combined with other renewable technologies like solar and wind to boost energy system flexibility and resilience.

Despite its significant potential for sustainability, several challenges still hinder the broader adoption of biogas technologies. These challenges include feedstock variability, technological issues, methane leakage, high capital costs, inconsistent policy frameworks, limited public knowledge, and insufficient infrastructure for upgrading and distributing biomethane. Future research is focusing more on integrating advanced anaerobic digestion technologies, digital monitoring systems, artificial intelligence, life-cycle assessment, and circular bioeconomy principles to improve the technical efficiency and overall sustainability of biogas systems. Strengthening policy

support, enhancing financing options, and promoting interdisciplinary collaboration are essential for maximizing biogas's contribution to sustainable energy transitions and global efforts to combat climate change.

Table 1: Summary

Author / Source	Year	Main Concepts & Contributions	Relevance to Biogas Systems
WCED (World Commission on Environment and Development)	1987	Introduced the core definition of sustainable development: meeting present needs without compromising future generations.	Formulates the overarching baseline rule that dictates how biogas resources must regenerate over time
Elkington	1997	Established the Three Pillars of Sustainability: environmental protection, economic viability, and social equity.	Provides the standard framework used to operationalize and evaluate the multi-dimensional benefits of biogas.
Scarlat et al.; Alengebawy et al.	2018; 2024	Addressed renewable energy production, waste management, greenhouse gas (GHG) mitigation, and resource recovery.	Identifies biogas as an essential system that links circular economy principles directly to global energy transitions.
Abanades et al.; Shah et al.	2022; 2024	Focused on continuous biomass resource regeneration and long-term renewable energy security.	Proves that biogas reliably replaces depleting, non-renewable fossil fuel energy streams while managing waste.

Anaerobic Digestion Technology

Anaerobic digestion (AD) is the core technology underpinning biogas production and has become one of the most widely adopted biological processes for converting biodegradable organic waste into renewable energy. The technology offers an environmentally sustainable approach to managing agricultural residues, livestock manure, municipal solid waste, food waste, industrial organic waste, and wastewater sludge while simultaneously producing biogas and nutrient-rich digestate. Compared with conventional waste disposal methods such as landfilling and incineration, anaerobic digestion provides a more sustainable alternative by reducing greenhouse gas emissions, recovering renewable energy, and promoting circular resource utilization (Mao et al., 2015; Scarlat et al., 2018; Logan et al., 2023).

Anaerobic digestion is a naturally occurring microbial process that decomposes organic matter in the absence of oxygen. The process involves a complex consortium of microorganisms that convert biodegradable substrates into methane-rich biogas through a series of biochemical reactions. The resulting biogas typically consists of 50–70% methane (CH₄), 30–50% carbon dioxide (CO₂), and trace amounts of hydrogen sulfide (H₂S), ammonia (NH₃), hydrogen (H₂), nitrogen (N₂), oxygen (O₂), and water vapor (Mao et al., 2015; Appels et al., 2011). Methane is the principal energy carrier responsible for the calorific value of biogas, making process optimization essential for maximizing energy recovery and improving system efficiency.

The anaerobic digestion process consists of four sequential biological stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Batstone et al., 2002; Appels et al., 2011). During hydrolysis, complex organic polymers such as carbohydrates, proteins, and lipids are broken down into soluble sugars, amino acids, and fatty acids by extracellular enzymes produced by hydrolytic bacteria. Hydrolysis is often regarded as the rate-limiting step when lignocellulosic biomass is used because cellulose and lignin exhibit strong structural resistance to microbial degradation (Mao et al., 2015).

Following hydrolysis, soluble organic compounds undergo acidogenesis, where fermentative microorganisms convert these intermediates into volatile fatty acids (VFAs), alcohols, hydrogen, carbon dioxide, and ammonia. Acidogenesis represents an essential intermediate stage because the generated VFAs serve as substrates for subsequent microbial reactions. However, excessive accumulation of VFAs can lower reactor pH and inhibit

methanogenic microorganisms, leading to process instability and reduced methane production (Appels et al., 2011).

The third stage, acetogenesis, converts volatile fatty acids and alcohols into acetate, carbon dioxide, and hydrogen through the activity of acetogenic bacteria. Since approximately 70% of methane originates from acetate metabolism, maintaining a balanced acetogenic microbial population is crucial for stable reactor performance. The final stage, methanogenesis, is carried out by methanogenic archaea that convert acetate, hydrogen, and carbon dioxide into methane. Methanogenesis is particularly sensitive to environmental conditions such as temperature, pH, ammonia concentration, and toxic compounds. Consequently, maintaining stable operating conditions is essential for maximizing methane yield and ensuring long-term digester performance (Batstone et al., 2002; Appels et al., 2011).

The efficiency of anaerobic digestion depends on numerous operational parameters that influence microbial activity and substrate degradation. Temperature is one of the most critical factors affecting biogas production. Anaerobic digesters generally operate under psychrophilic (<25°C), mesophilic (30–40°C), or thermophilic (50–60°C) conditions. Mesophilic digestion is the most widely adopted because it provides stable microbial communities, lower operational costs, and reliable methane production. Thermophilic digestion offers faster degradation rates, higher pathogen removal, and increased methane productivity but requires greater energy input and exhibits higher sensitivity to operational disturbances (Khalid et al., 2011; Mao et al., 2015).

Besides temperature, pH significantly influences microbial activity throughout the digestion process. Most methanogenic microorganisms perform optimally within a pH range of 6.8–7.5, whereas acidic conditions caused by volatile fatty acid accumulation inhibit methane production and destabilize the digestion process. Other important operational parameters include hydraulic retention time (HRT), organic loading rate (OLR), carbon-to-nitrogen (C/N) ratio, substrate composition, moisture content, mixing intensity, and nutrient availability. Optimizing these parameters improves methane yield, enhances volatile solids degradation, and minimizes process failures (Khalid et al., 2011; Logan et al., 2023).

Feedstock characteristics also play a fundamental role in determining anaerobic digestion performance. Livestock manure remains one of the most widely used substrates because of its stable composition and abundant microbial inoculum. Agricultural residues such as rice straw, wheat straw, maize silage, and sugarcane bagasse represent significant renewable biomass resources but often require pretreatment because of their high lignocellulosic content. Municipal food waste has attracted increasing attention due to its high biodegradability and methane potential, although rapid acidification may affect reactor stability. Sewage sludge, industrial organic waste, and agro-industrial residues also contribute substantially to global biogas production, particularly within integrated waste management systems (Scarlat et al., 2018; Logan et al., 2023).

To improve digestion efficiency, researchers have increasingly adopted co-digestion, which involves simultaneously digesting two or more complementary feedstocks. Co-digestion improves nutrient balance, optimizes the carbon-to-nitrogen ratio, enhances microbial diversity, increases methane yield, and reduces process inhibition compared with mono-digestion. Common substrate combinations include livestock manure with food waste, sewage sludge with agricultural residues, and industrial organic waste with municipal organic waste. Numerous studies have demonstrated that co-digestion significantly improves reactor stability and biogas productivity while expanding the range of biodegradable waste streams suitable for renewable energy production (Mata-Alvarez et al., 2014; Mao et al., 2015).

Recent technological developments have further improved anaerobic digestion efficiency through advanced pretreatment methods, reactor configurations, and process monitoring systems. Physical pretreatments such as mechanical milling, thermal hydrolysis, microwave irradiation, and ultrasonic treatment increase substrate biodegradability by disrupting complex biomass structures. Chemical pretreatments involving alkaline or acid hydrolysis improve lignocellulosic degradation, whereas biological pretreatments utilize fungi or specialized microorganisms to accelerate biomass decomposition. These approaches collectively enhance hydrolysis efficiency and increase methane production, particularly for agricultural residues and lignocellulosic biomass (Kumar et al., 2020; Logan et al., 2023).

Advances in reactor technology have also contributed to higher biogas productivity and operational stability. Common reactor designs include continuously stirred tank reactors (CSTRs), plug-flow digesters, upflow anaerobic sludge blanket (UASB) reactors, anaerobic sequencing batch reactors (ASBRs), and anaerobic membrane bioreactors (AnMBRs). Reactor selection depends on feedstock characteristics, solids concentration, retention time, operational scale, and desired energy output. Recent innovations integrating membrane separation, real-time monitoring sensors, artificial intelligence, and machine learning have enabled improved process control, predictive maintenance, and optimization of methane production under varying operational conditions (Logan et al., 2023; Alengebawy et al., 2024).

Biogas upgrading technologies have become increasingly important as countries expand biomethane utilization within transportation and natural gas sectors. Raw biogas contains impurities such as carbon dioxide, hydrogen sulfide, moisture, and siloxanes that reduce fuel quality and limit its direct application. Upgrading technologies—including water scrubbing, pressure swing adsorption, membrane separation, chemical absorption, and cryogenic separation—remove these impurities to produce biomethane with methane concentrations exceeding 95%. Upgraded biomethane can be injected into natural gas grids, compressed as vehicle fuel, or used in industrial applications, thereby increasing the economic value and market competitiveness of anaerobic digestion systems (Scarlat et al., 2018; IEA Bioenergy, 2022).

Despite substantial technological progress, several challenges continue to constrain the large-scale implementation of anaerobic digestion. Feedstock variability, ammonia inhibition, volatile fatty acid accumulation, methane leakage, digester foaming, high capital investment, operational complexity, and inadequate technical expertise remain significant barriers to efficient biogas production. Moreover, inconsistent policy support, limited financing, and insufficient infrastructure for biomethane distribution restrict commercial deployment in many developing countries. Future research increasingly focuses on integrating digital technologies, advanced microbial engineering, genomic analysis, artificial intelligence, and life-cycle assessment to optimize anaerobic digestion performance and enhance the sustainability of biogas production systems (Alengebawy et al., 2024; Logan et al., 2023).

Overall, anaerobic digestion remains the cornerstone technology for sustainable biogas production. Continued advances in feedstock pretreatment, microbial ecology, reactor engineering, process optimization, and biomethane upgrading are expected to improve energy conversion efficiency, economic viability, and environmental performance. These developments position anaerobic digestion as a critical technology supporting renewable energy expansion, circular economy implementation, and global decarbonization strategies.

Feedstock for Biogas Production

Feedstock selection is one of the most critical determinants of anaerobic digestion performance and biogas production efficiency. The quantity and quality of feedstock directly influence methane yield, process stability, nutrient balance, digestate characteristics, and the overall economic viability of biogas systems. Feedstocks for anaerobic digestion comprise a wide range of biodegradable organic materials generated from agricultural, municipal, industrial, and domestic activities. These materials are rich in carbohydrates, proteins, lipids, and other biodegradable compounds that can be converted into methane through microbial degradation under anaerobic conditions (Mao et al., 2015; Scarlat et al., 2018). The increasing availability of organic waste worldwide presents significant opportunities for expanding biogas production while simultaneously addressing waste management challenges and supporting circular economy initiatives (Al Seadi et al., 2018).

Agricultural Residues

Agricultural residues represent one of the largest renewable biomass resources available for biogas production. Crop residues such as rice straw, wheat straw, maize stover, corn silage, sugarcane bagasse, barley straw, and oil palm residues are generated in substantial quantities worldwide and often remain underutilized or are disposed of through open-field burning. Utilizing these residues for anaerobic digestion reduces environmental pollution while producing renewable energy and improving waste management practices (Scarlat et al., 2018;

Logan et al., 2023).

Despite their abundance, agricultural residues present several technical challenges because they contain high concentrations of lignocellulosic materials composed of cellulose, hemicellulose, and lignin. Lignin forms a protective barrier around cellulose fibers, limiting microbial access during hydrolysis and reducing methane production. Consequently, various pretreatment technologies—including mechanical size reduction, steam explosion, alkaline treatment, acid hydrolysis, and biological pretreatment—have been developed to enhance substrate biodegradability and improve methane yield (Kumar et al., 2020). Research indicates that appropriate pretreatment can substantially increase biogas production while shortening digestion time and improving substrate conversion efficiency (Mao et al., 2015).

Livestock Manure

Livestock manure remains one of the most widely utilized feedstocks for anaerobic digestion because of its continuous availability, balanced nutrient composition, and naturally occurring anaerobic microorganisms. Cattle manure, pig slurry, poultry litter, sheep manure, and goat manure are commonly used in commercial and farm-scale digesters worldwide. Besides renewable energy production, manure digestion reduces methane emissions associated with conventional manure storage, minimizes unpleasant odors, destroys pathogenic microorganisms, and produces nutrient-rich digestate suitable for agricultural application (Holm-Nielsen et al., 2009; Scarlat et al., 2018).

The methane potential of livestock manure depends on animal species, feeding practices, moisture content, and manure management systems. Dairy cattle manure generally provides stable digestion performance because of its relatively balanced carbon-to-nitrogen (C/N) ratio and buffering capacity. In contrast, poultry manure often contains high nitrogen concentrations that may cause ammonia inhibition during anaerobic digestion if not properly managed (Khalid et al., 2011). Consequently, manure is frequently combined with carbon-rich substrates through co-digestion to optimize nutrient balance and improve methane production.

Food Waste

Food waste has become an increasingly important feedstock because of its high organic content and excellent biodegradability. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced globally is lost or wasted annually, creating significant environmental and economic challenges. Instead of disposing food waste in landfills where uncontrolled anaerobic decomposition produces methane emissions, anaerobic digestion converts these materials into renewable energy while supporting sustainable waste management (FAO, 2019).

Food waste generally contains large amounts of carbohydrates, proteins, and lipids that provide high methane potential compared with many agricultural residues. Studies have reported methane yields ranging from 400 to 700 m³ CH₄ per tonne of volatile solids depending on substrate composition (Mao et al., 2015). However, rapid degradation of food waste often causes excessive accumulation of volatile fatty acids (VFAs), resulting in pH reduction and inhibition of methanogenic microorganisms. To overcome these challenges, food waste is frequently co-digested with livestock manure or sewage sludge, improving process stability and methane productivity (Mata-Alvarez et al., 2014).

Municipal Solid Waste

The organic fraction of municipal solid waste (MSW) represents another major feedstock for biogas production. Urbanization and population growth have significantly increased municipal waste generation worldwide, placing considerable pressure on landfill capacity and environmental management systems. Organic municipal waste—including kitchen waste, market waste, green waste, and biodegradable household refuse—can be effectively treated through anaerobic digestion, thereby reducing landfill dependency while generating renewable energy (Scarlat et al., 2018).

The composition of municipal solid waste varies considerably depending on socio-economic conditions, dietary habits, climate, and waste collection practices. Therefore, effective source separation and waste sorting are essential for removing plastics, metals, and other non-biodegradable contaminants that negatively affect digester performance. Numerous European countries have successfully integrated anaerobic digestion into municipal waste management systems by combining source-separated organic waste collection with centralized biogas facilities (European Biogas Association, 2023).

Sewage Sludge

Wastewater treatment plants generate substantial quantities of sewage sludge that require environmentally sustainable disposal methods. Anaerobic digestion has become one of the most widely adopted technologies for sludge stabilization because it simultaneously reduces sludge volume, destroys pathogens, minimizes odors, and produces renewable biogas (Appels et al., 2011).

Primary sludge generally exhibits higher methane potential than waste activated sludge because it contains larger proportions of readily biodegradable organic matter. Nevertheless, wastewater treatment facilities increasingly adopt co-digestion strategies by combining sewage sludge with food waste or industrial organic waste to increase organic loading rates and improve methane yields. Such integrated approaches enhance both energy recovery and overall treatment efficiency (Logan et al., 2023).

Industrial Organic Waste

Numerous agro-industrial sectors generate biodegradable organic waste suitable for anaerobic digestion. These include dairy processing wastewater, brewery spent grains, distillery residues, sugar industry waste, fruit and vegetable processing residues, palm oil mill effluent (POME), slaughterhouse waste, and paper mill sludge. These materials often possess high organic loading rates and excellent biodegradability, making them attractive feedstocks for renewable energy production (Al Seadi et al., 2018).

Palm oil mill effluent has attracted particular attention in Southeast Asia because Malaysia and Indonesia are among the world's largest palm oil producers. Untreated POME contains high concentrations of organic matter that can generate significant methane emissions if discharged into open ponds. Anaerobic digestion of POME captures methane for renewable electricity generation while reducing environmental pollution and improving wastewater management practices (Lam et al., 2020).

Co-Digestion of Multiple Feedstocks

Recent research has increasingly emphasized anaerobic co-digestion, which involves simultaneously digesting two or more complementary feedstocks. Co-digestion improves nutrient balance, optimizes carbon-to-nitrogen ratios, dilutes toxic compounds, enhances microbial diversity, and increases methane production compared with mono-digestion (Mata-Alvarez et al., 2014).

Common substrate combinations include livestock manure with food waste, sewage sludge with agricultural residues, poultry manure with crop straw, and municipal organic waste with industrial wastewater. Numerous studies have demonstrated that co-digestion enhances reactor stability, improves volatile solids degradation, reduces process inhibition, and increases methane yields by 20–60% depending on substrate characteristics (Mao et al., 2015; Logan et al., 2023).

Feedstock Sustainability

Beyond technical performance, feedstock selection significantly influences the environmental, economic, and social sustainability of biogas systems. Sustainable feedstock utilization prioritizes organic wastes and agricultural residues rather than dedicated energy crops to avoid competition with food production, excessive

land use, and biodiversity loss. Waste-derived feedstocks promote circular economy principles by transforming organic waste into renewable energy and nutrient-rich digestate while minimizing greenhouse gas emissions and landfill disposal (Behzadian et al., 2023).

Economic sustainability depends on feedstock availability, transportation distance, seasonal variability, storage requirements, and collection logistics. Reliable feedstock supply chains reduce operational risks and improve long-term profitability. Social sustainability is strengthened through farmer participation, municipal waste collection programs, industrial collaboration, and community engagement, all of which enhance resource efficiency and support local economic development (Scarlat et al., 2018).

Overall, feedstock selection remains one of the most important factors determining the technical efficiency, environmental performance, and economic feasibility of anaerobic digestion systems. Future research increasingly focuses on optimizing feedstock combinations, improving pretreatment technologies, integrating digital monitoring systems, and developing sustainable biomass supply chains that maximize renewable energy production while supporting circular bioeconomy objectives.

Environmental Benefits of Biogas

The growing global emphasis on environmental sustainability has significantly increased interest in biogas as an environmentally friendly renewable energy source. Unlike fossil fuels, biogas is produced from biodegradable organic materials through anaerobic digestion, transforming waste into valuable energy while reducing environmental pollution. Consequently, biogas contributes simultaneously to climate change mitigation, sustainable waste management, resource recovery, and circular economy implementation. Numerous studies have identified environmental sustainability as one of the principal drivers for the adoption of biogas technologies worldwide (Holm-Nielsen et al., 2009; Scarlat et al., 2018; Logan et al., 2023).

Greenhouse Gas Emission Reduction

One of the most significant environmental benefits of biogas is its capacity to reduce greenhouse gas (GHG) emissions. Organic waste disposed of in landfills, manure lagoons, and uncontrolled waste dumps naturally decomposes under anaerobic conditions, releasing methane (CH_4), a greenhouse gas with a global warming potential approximately 28–34 times greater than carbon dioxide (CO_2) over a 100-year period (IPCC, 2021). Anaerobic digestion captures this methane before it escapes into the atmosphere and converts it into renewable energy, thereby substantially reducing overall greenhouse gas emissions.

Furthermore, biogas replaces fossil fuels such as coal, diesel, natural gas, and liquefied petroleum gas (LPG) for electricity generation, heating, and transportation. This substitution decreases carbon dioxide emissions associated with conventional energy production while supporting national carbon neutrality strategies. Life-cycle assessment (LCA) studies consistently demonstrate that biogas systems produce considerably lower net greenhouse gas emissions than fossil fuel-based energy systems, particularly when agricultural residues, livestock manure, food waste, and municipal organic waste are utilized as feedstocks (Mao et al., 2015; Al Seadi et al., 2018). Consequently, biogas has become an important technology for achieving the greenhouse gas reduction targets established under the Paris Agreement and various national climate action plans.

Sustainable Waste Management

Biogas technology plays a vital role in improving sustainable waste management by converting biodegradable waste into renewable energy instead of disposing it in landfills or open dumping sites. Globally, increasing urbanization, industrialization, and population growth have resulted in substantial increases in municipal solid waste, agricultural residues, livestock manure, and industrial organic waste. Conventional waste disposal methods frequently generate environmental problems, including groundwater contamination, unpleasant odors, disease transmission, and uncontrolled greenhouse gas emissions (Kaza et al., 2018).

Anaerobic digestion provides an environmentally sustainable alternative by reducing waste volume while recovering energy and valuable nutrients. Organic waste that would otherwise contribute to landfill methane emissions is transformed into biogas and digestate, minimizing environmental impacts while improving resource efficiency. Many European countries have successfully integrated anaerobic digestion into municipal waste management systems through source-separated organic waste collection and centralized digestion facilities, significantly reducing landfill dependence and supporting national recycling targets (European Biogas Association, 2023).

Resource Recovery and Circular Economy

The circular economy emphasizes maximizing resource utilization by minimizing waste generation and promoting material recovery throughout product life cycles. Biogas production aligns closely with these principles because anaerobic digestion converts organic waste into multiple valuable products, including renewable energy, biomethane, and nutrient-rich digestate. Rather than treating organic waste as an environmental liability, anaerobic digestion transforms it into economic and environmental assets (Geissdoerfer et al., 2017).

Digestate represents one of the most valuable by-products of anaerobic digestion. It contains significant concentrations of nitrogen, phosphorus, potassium, and organic matter that improve soil fertility and crop productivity. The application of digestate as biofertilizer reduces dependence on synthetic fertilizers, lowers energy consumption associated with fertilizer manufacturing, and promotes sustainable agricultural practices. Nutrient recycling through digestate application also minimizes nutrient losses to water bodies, reducing the risks of eutrophication and improving long-term soil health (Holm-Nielsen et al., 2009; Al Seadi et al., 2018).

Reduction of Air and Water Pollution

Biogas systems contribute significantly to reducing both air and water pollution. Open decomposition of livestock manure and organic waste generates unpleasant odors, ammonia emissions, volatile organic compounds (VOCs), and airborne pathogens that negatively affect environmental quality and public health. Anaerobic digestion substantially reduces these emissions by stabilizing organic waste under controlled conditions, thereby improving air quality around agricultural and municipal waste management facilities (Appels et al., 2011).

Similarly, untreated agricultural runoff, livestock manure, and industrial organic wastewater contain high concentrations of organic pollutants, nutrients, and pathogens that contaminate rivers, lakes, and groundwater resources. Anaerobic digestion lowers chemical oxygen demand (COD), biological oxygen demand (BOD), and pathogen levels before waste disposal or land application. Consequently, biogas technology contributes to improved water quality while reducing environmental degradation associated with untreated organic waste (Logan et al., 2023).

Soil Conservation and Sustainable Agriculture

The environmental benefits of biogas extend to sustainable agriculture through improved soil management and nutrient recycling. Continuous application of chemical fertilizers often degrades soil structure, reduces microbial diversity, and increases nutrient leaching into surrounding ecosystems. Digestate produced during anaerobic digestion contains stabilized organic matter and essential plant nutrients that improve soil physical, chemical, and biological properties (Möller & Müller, 2012).

Regular digestate application enhances soil organic carbon, improves water retention capacity, stimulates beneficial microbial activity, and increases long-term agricultural productivity. Moreover, replacing synthetic fertilizers with digestate reduces fossil energy consumption during fertilizer production while lowering greenhouse gas emissions associated with nitrogen fertilizer manufacturing. These environmental advantages support regenerative agricultural practices and strengthen the sustainability of integrated farming systems.

Biodiversity Conservation and Renewable Energy Transition

The adoption of biogas technologies indirectly contributes to biodiversity conservation by reducing reliance on fossil fuels and unsustainable biomass harvesting. In many developing countries, rural households continue to depend on fuelwood for cooking and heating, contributing to deforestation, habitat degradation, and loss of biodiversity. Household biogas systems provide a clean alternative cooking fuel that reduces fuelwood consumption while improving indoor air quality and protecting forest ecosystems (Bond & Templeton, 2011).

At the national level, integrating biogas into renewable energy portfolios diversifies energy supply while supporting the transition toward low-carbon energy systems. Unlike intermittent renewable sources such as solar and wind, biogas provides dispatchable energy that can generate electricity continuously, thereby improving energy system reliability and facilitating greater penetration of variable renewable energy technologies. This complementary role enhances energy security while reducing environmental pressures associated with fossil fuel extraction and combustion (Scarlat et al., 2018).

Environmental Challenges and Future Perspectives

Despite its considerable environmental advantages, biogas production also presents several environmental challenges that require careful management. Methane leakage during biogas production, upgrading, storage, and transportation can reduce overall climate benefits if not adequately controlled. Similarly, inappropriate digestate management may contribute to nutrient runoff, ammonia volatilization, and groundwater contamination. Feedstock transportation over long distances also increases energy consumption and greenhouse gas emissions, potentially reducing the environmental performance of biogas systems (Mao et al., 2015; Logan et al., 2023).

Future research increasingly focuses on improving environmental performance through advanced methane monitoring technologies, precision digestate management, life-cycle assessment, digital monitoring systems, and artificial intelligence for process optimization. Integrating anaerobic digestion with carbon capture and utilization (CCU), biochar production, hydrogen generation, and nutrient recovery technologies also represent promising opportunities for enhancing the environmental sustainability of biogas systems within emerging circular bioeconomy frameworks (Alengebawy et al., 2024).

Overall, biogas offers substantial environmental benefits by mitigating greenhouse gas emissions, improving waste management, promoting resource recovery, reducing pollution, supporting sustainable agriculture, and facilitating renewable energy transitions. These multidimensional environmental advantages position anaerobic digestion as a key technology for achieving global sustainability objectives, advancing circular economy strategies, and supporting long-term climate change mitigation.

Economic and Social Perspectives

The successful deployment of biogas technology depends not only on its technical performance and environmental benefits but also on its economic feasibility and social acceptance. Economic and social factors significantly influence investment decisions, technology adoption, long-term operation, and policy implementation. Although anaerobic digestion has demonstrated considerable potential for renewable energy generation and sustainable waste management, its widespread adoption is often constrained by high capital costs, operational challenges, financing limitations, policy uncertainty, and varying levels of public awareness. Consequently, understanding the economic and social dimensions of biogas development is essential for promoting sustainable energy transitions and maximizing the contribution of biogas to circular economy objectives (Scarlat et al., 2018; Behzadian et al., 2023).

Economic Viability of Biogas Systems

Economic viability is one of the primary determinants influencing investment in biogas projects. The financial performance of anaerobic digestion systems depends on several interrelated factors, including feedstock availability, plant capacity, capital investment, operational and maintenance costs, energy prices, government

incentives, and revenues generated from electricity, biomethane, heat, carbon credits, and digestate utilization (Holm-Nielsen et al., 2009; Mao et al., 2015).

Large-scale commercial biogas plants generally benefit from economies of scale, allowing lower production costs per unit of energy and higher operational efficiency. In contrast, small-scale household and farm-based digesters require lower investment but often generate limited financial returns because of reduced energy production capacity. The economic feasibility of both systems is strongly influenced by local feedstock availability and transportation costs. Feedstocks located near digestion facilities reduce logistics expenses and improve overall project profitability (Scarlat et al., 2018).

Several techno-economic studies have demonstrated that biogas projects become increasingly competitive when multiple revenue streams are considered. Besides renewable electricity generation, income may be obtained through biomethane sales, combined heat and power (CHP) utilization, organic fertilizer production, waste treatment fees, and greenhouse gas emission credits. These diversified income sources improve project resilience and reduce dependence on fluctuating energy markets (Al Seadi et al., 2018; Logan et al., 2023).

Investment Costs and Financial Barriers

Despite their long-term environmental and economic benefits, biogas projects often require substantial initial capital investment. Construction of anaerobic digestion facilities involves significant expenditure for digesters, feedstock handling systems, gas storage units, upgrading equipment, electricity generation systems, monitoring technologies, and supporting infrastructure. Additional costs arise from land acquisition, engineering design, permitting, maintenance, labor, and feedstock transportation (Mao et al., 2015).

These high upfront costs remain one of the most significant barriers to biogas development, particularly in developing countries where access to affordable financing is limited. Smallholder farmers and local communities frequently lack sufficient capital or collateral to obtain commercial loans for biogas installations. Furthermore, financial institutions often perceive renewable energy investments as relatively high-risk because of technological uncertainty, changing government policies, and fluctuating energy prices (Behzadian et al., 2023). To overcome these constraints, many governments have introduced financial support mechanisms such as investment grants, low-interest loans, tax incentives, feed-in tariffs, renewable energy certificates, and carbon pricing schemes. Evidence from Germany, Denmark, Sweden, and the Netherlands indicates that consistent policy incentives significantly improve investment confidence and accelerate biogas deployment (Scarlat et al., 2018; European Biogas Association, 2023).

Employment and Rural Economic Development

Biogas development contributes substantially to local and regional economic growth through employment generation and rural development. The construction, operation, and maintenance of anaerobic digestion facilities create direct employment opportunities for engineers, technicians, plant operators, waste collection personnel, maintenance specialists, transport providers, and environmental consultants. Indirect employment also arises through equipment manufacturing, agricultural services, feedstock supply chains, and fertilizer distribution networks (Holm-Nielsen et al., 2009).

Agricultural biogas projects offer additional income opportunities for farmers by transforming livestock manure, crop residues, and agricultural by-products into renewable energy. Instead of treating organic residues as waste, farmers can generate revenue through electricity sales, biomethane production, digestate commercialization, and participation in carbon credit markets. These diversified income streams improve farm resilience while reducing dependence on conventional agricultural commodities (Bond & Templeton, 2011).

The establishment of community-based biogas projects further stimulates local economic development by encouraging cooperative ownership models and strengthening local energy independence. Rural communities benefit from reduced energy expenditures, improved waste management services, enhanced agricultural

productivity, and increased employment opportunities, contributing to broader socio-economic development objectives (IRENA, 2022).

Energy Security and Economic Resilience

Biogas contributes significantly to national energy security by diversifying energy sources and reducing dependence on imported fossil fuels. Many countries remain vulnerable to fluctuations in global oil and natural gas markets, exposing their economies to energy price volatility and supply disruptions. Locally produced biogas offers a decentralized and renewable alternative that strengthens domestic energy production while increasing resilience against external energy shocks (International Energy Agency [IEA], 2023).

Unlike intermittent renewable energy sources such as wind and solar power, biogas provides continuous and dispatchable energy generation. This characteristic enables biogas facilities to support electricity grid stability while complementing other renewable technologies. The integration of biomethane into existing natural gas infrastructure further enhances energy flexibility and supports the decarbonization of industrial, residential, and transportation sectors (Scarlat et al., 2018).

Social Acceptance and Public Awareness

The long-term success of biogas technology depends heavily on public acceptance and stakeholder engagement. Community support influences project planning, facility construction, feedstock collection systems, and operational continuity. Public perceptions of odor emissions, traffic movement, environmental risks, and land use frequently affect the willingness of local communities to support new anaerobic digestion facilities (Wüstenhagen et al., 2007).

Conversely, numerous studies indicate that public acceptance increases when communities recognize the environmental, economic, and social benefits associated with biogas production. Improved waste management, renewable energy generation, employment creation, reduced greenhouse gas emissions, and enhanced local energy security positively influence stakeholder perceptions. Public participation throughout project planning and implementation also improves transparency and strengthens trust among local stakeholders (Behzadian et al., 2023).

Education and awareness campaigns play an essential role in promoting community understanding of anaerobic digestion technologies. Training programmes for farmers, municipal authorities, engineers, and local residents improve technical knowledge, encourage proper feedstock management, and increase confidence in biogas technologies. Universities, research institutions, and extension agencies therefore serve important functions in disseminating knowledge and supporting technology transfer.

Policy, Governance, and Institutional Support

Government policies represent one of the most influential drivers of biogas development. Supportive regulatory frameworks encourage investment, facilitate technological innovation, and create stable market conditions for renewable energy. Successful biogas industries in countries such as Germany, Denmark, and Sweden have been largely attributed to long-term renewable energy policies, feed-in tariffs, investment subsidies, renewable fuel standards, and carbon reduction targets (Scarlat et al., 2018).

Conversely, inconsistent regulations, complex permitting procedures, unclear environmental standards, and policy uncertainty discourage private investment and delay project implementation. Institutional coordination among environmental agencies, energy regulators, agricultural ministries, and local governments is therefore essential for creating integrated policy frameworks that promote sustainable biogas development (European Biogas Association, 2023).

International organizations, including the International Renewable Energy Agency (IRENA), the International

Energy Agency (IEA), and the Food and Agriculture Organization (FAO), have emphasized the importance of supportive governance, capacity building, and international collaboration for expanding global biogas deployment. Their recommendations highlight the need for harmonized policies that integrate renewable energy, waste management, agriculture, and climate change mitigation objectives.

Socio-Economic Challenges and Future Directions

Despite substantial progress, several socio-economic barriers continue to constrain the expansion of biogas technologies. High investment costs, limited access to financing, inadequate technical expertise, insufficient policy support, fragmented biomass supply chains, low public awareness, and market uncertainty remain major obstacles, particularly in developing economies (Behzadian et al., 2023).

Future research increasingly emphasizes innovative financing mechanisms such as green bonds, public-private partnerships, carbon finance, and climate investment funds to improve project affordability. Digital technologies, including artificial intelligence, Internet of Things (IoT)-based monitoring systems, and predictive analytics, are also expected to reduce operational costs and improve plant efficiency. Additionally, stronger stakeholder engagement, community participation, educational programmes, and integrated policy frameworks will be essential for increasing public acceptance and ensuring the long-term sustainability of biogas systems.

Overall, the economic and social dimensions of biogas development are closely interconnected with technical performance and environmental sustainability. Economically viable projects supported by stable policy frameworks, diversified revenue streams, and effective stakeholder engagement are more likely to achieve long-term success. Consequently, integrated approaches that simultaneously address financial, institutional, technological, and social factors are necessary to accelerate biogas deployment and support the global transition toward sustainable, low-carbon energy systems.

Research Gaps and Conceptual Foundation

The existing body of literature demonstrates that biogas technology has received increasing scholarly attention due to its significant contributions to renewable energy generation, sustainable waste management, greenhouse gas mitigation, and circular economy development. Previous studies have extensively examined anaerobic digestion processes, feedstock optimization, reactor technologies, life cycle assessment, techno-economic analysis, digestate utilization, and policy frameworks (Mao et al., 2015; Scarlat et al., 2018; Logan et al., 2023). Although these studies have substantially advanced scientific understanding of biogas systems, the literature remains fragmented across multiple disciplines, including environmental science, engineering, agriculture, economics, energy policy, and sustainability studies. Consequently, an integrated understanding of the multidimensional factors influencing biogas development is still limited.

One of the most significant research gaps concerns the fragmented assessment of sustainability dimensions. Most existing studies investigate technical performance, economic feasibility, environmental impacts, or social acceptance independently, with relatively few studies examining how these dimensions interact to influence the overall sustainability and long-term success of biogas systems. Technical studies primarily focus on improving methane yield, reactor performance, feedstock pretreatment, microbial activity, and process optimization (Appels et al., 2011; Kumar et al., 2020). Economic research generally emphasizes investment costs, profitability, financial incentives, and market development (Holm-Nielsen et al., 2009). Environmental studies frequently evaluate greenhouse gas emissions, waste reduction, nutrient recovery, and life-cycle impacts, while social research concentrates on stakeholder engagement, public acceptance, institutional capacity, and policy implementation (Wüstenhagen et al., 2007; Behzadian et al., 2023). However, these dimensions are inherently interconnected and should be evaluated collectively rather than independently.

A second research gap relates to the geographical concentration of existing biogas research. Much of the current literature originates from developed economies, particularly Germany, Denmark, Sweden, Italy, China, and the Netherlands, where supportive renewable energy policies, advanced infrastructure, and mature biogas industries

have facilitated technological development (Scarlat et al., 2018). Comparatively fewer studies examine biogas implementation in developing countries across Southeast Asia, Sub-Saharan Africa, Latin America, and parts of South Asia, despite these regions possessing abundant biomass resources and significant renewable energy potential (Bond & Templeton, 2011). Differences in institutional capacity, financing mechanisms, agricultural practices, waste management systems, and socio-economic conditions suggest that findings from developed countries cannot always be generalized to emerging economies. Additional comparative research is therefore needed to identify context-specific factors influencing biogas adoption across diverse geographical settings.

Another important gap concerns the limited integration of circular economy principles within biogas research. Although anaerobic digestion is widely recognized as a waste-to-energy technology, relatively few studies comprehensively examine its role in broader circular bioeconomy systems. Existing research frequently focuses on renewable energy production while paying comparatively less attention to nutrient recycling, industrial symbiosis, cascading biomass utilization, resource efficiency, and value chain integration. Future studies should therefore investigate how biogas technologies can be integrated with agriculture, wastewater treatment, food processing, carbon capture, biofertilizer production, and other renewable technologies to maximize resource recovery and support sustainable bioeconomy development (Geissdoerfer et al., 2017; European Biogas Association, 2023).

The literature also reveals methodological limitations in evaluating the sustainability of biogas systems. Numerous studies employ life cycle assessment (LCA), techno-economic analysis (TEA), or environmental impact assessment independently, often neglecting broader sustainability indicators such as governance quality, institutional effectiveness, community participation, policy consistency, and social equity (Behzadian et al., 2023). Furthermore, inconsistencies in system boundaries, functional units, feedstock assumptions, and performance indicators make comparisons across studies difficult. Greater methodological standardization and the integration of environmental, economic, technical, and social assessment tools would enhance the robustness and comparability of future research.

Technological innovation represents another emerging research area requiring greater scholarly attention. Recent advances in artificial intelligence, machine learning, digital twins, Internet of Things (IoT)-based monitoring systems, genomic analysis, predictive modelling, and automated process control offer significant opportunities to improve anaerobic digestion efficiency and operational reliability. Nevertheless, empirical evidence regarding the practical implementation and long-term performance of these digital technologies remains relatively limited. Future investigations should evaluate their effectiveness under commercial operating conditions and explore their contribution to improving methane yield, reducing operational costs, minimizing methane leakage, and enhancing predictive maintenance (Logan et al., 2023).

Policy and governance also remain underexplored within the biogas literature. Although numerous studies recognize government incentives as important drivers of renewable energy development, comparatively fewer investigations examine how regulatory consistency, institutional coordination, stakeholder collaboration, financing mechanisms, and governance quality collectively influence biogas deployment. Comparative policy analyses across countries with varying institutional arrangements would provide valuable insights for improving renewable energy governance and facilitating technology diffusion (International Energy Agency [IEA], 2023). Based on these identified research gaps, this study proposes that sustainable biogas development should be understood as the outcome of interactions among four interdependent sustainability dimensions: technical capability, economic viability, environmental sustainability, and social acceptance. Rather than functioning independently, these dimensions reinforce one another and collectively determine the long-term performance and scalability of biogas systems. Technical innovation improves operational efficiency and methane production, which enhances economic returns. Economic viability supports continued investment in technological improvements and environmental protection measures. Environmental performance strengthens public confidence and policy support, while social acceptance facilitates stakeholder participation, institutional collaboration, and long-term implementation. These dynamic relationships indicate that improvements in one dimension may positively influence outcomes in the others, thereby creating reinforcing sustainability benefits.

Drawing upon sustainability theory (Elkington, 1997), circular economy principles (Geissdoerfer et al., 2017), and socio-technical transition theory (Geels, 2002), this study develops an integrated conceptual foundation for analysing biogas energy systems. Sustainability theory provides the overarching framework for balancing environmental, economic, and social objectives. Circular economy principles emphasize waste valorization, resource recovery, and closed-loop material flows, which are central characteristics of anaerobic digestion. Socio-technical transition theory explains how technological innovation, institutional arrangements, market mechanisms, and societal acceptance interact to facilitate the transition from conventional fossil fuel systems toward renewable energy technologies. Integrating these complementary theoretical perspectives provides a comprehensive framework for understanding the complexity of biogas development across multiple sectors and geographical contexts.

Building upon this conceptual foundation, the subsequent sections of this review synthesize evidence from the selected literature to examine how technical, economic, environmental, and social factors interact to influence biogas development. The findings will be used to develop an integrated conceptual framework and a series of research propositions that explain the multidimensional relationships underpinning sustainable biogas energy systems. This framework is expected to contribute to both theory and practice by supporting future empirical research, informing policy formulation, and guiding strategic decision-making for renewable energy development and circular bioeconomy implementation.

Future Research

The systematic review demonstrates that although significant progress has been achieved in biogas technology over the past decade, several knowledge gaps remain that require further investigation. Existing studies have substantially improved understanding of anaerobic digestion processes, feedstock optimization, reactor design, environmental performance, and economic feasibility. However, future research should adopt a more integrated and interdisciplinary perspective that considers the interactions among technical, economic, environmental, institutional, and social dimensions. Addressing these research gaps will strengthen the role of biogas in supporting renewable energy transitions, circular economy implementation, and global climate change mitigation (Behzadian et al., 2023; Logan et al., 2023).

One of the most important priorities is the development of next-generation anaerobic digestion technologies that improve methane productivity, operational stability, and energy conversion efficiency. Although numerous studies have investigated feedstock pretreatment, microbial community dynamics, and reactor optimization, additional research is needed to improve digestion performance for lignocellulosic biomass, mixed organic wastes, and industrial residues. Future studies should evaluate advanced pretreatment methods, including biological, thermal, chemical, and electrochemical technologies, while simultaneously assessing their economic feasibility and environmental impacts under commercial operating conditions (Kumar et al., 2020; Mao et al., 2015).

The application of digital technologies represents another promising research direction. Recent advances in artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), digital twins, and advanced sensor technologies have created new opportunities for real-time monitoring, predictive maintenance, and process optimization in anaerobic digestion systems. However, empirical studies evaluating the practical implementation of these technologies remain limited. Future research should investigate AI-driven predictive models for methane production, early fault detection, automated process control, and optimization of operational parameters across different feedstock types and reactor configurations (Logan et al., 2023).

Another important area concerns feedstock diversification and sustainable biomass supply chains. Most existing studies focus on livestock manure, food waste, sewage sludge, and agricultural residues, whereas many region-specific biomass resources remain underexplored. Future research should investigate the biogas potential of emerging feedstocks such as algae, invasive plant species, agro-industrial residues, municipal green waste, textile waste, biodegradable packaging materials, and mixed organic waste streams. In addition, comprehensive assessments of feedstock logistics, seasonal availability, transportation systems, storage requirements, and

supply chain resilience are required to improve the long-term sustainability of commercial biogas production (Scarlat et al., 2018).

The review also highlights the need for more comprehensive life cycle sustainability assessment. While numerous studies employ Life Cycle Assessment (LCA) to quantify environmental impacts, relatively few integrate LCA with Techno-Economic Analysis (TEA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC). Future investigations should adopt multi-dimensional sustainability assessment frameworks that simultaneously evaluate environmental performance, economic viability, resource efficiency, social acceptance, governance quality, and policy effectiveness. Such integrated approaches would provide more comprehensive decision-support tools for policymakers and investors (Behzadian et al., 2023).

Further research is also required on biomethane upgrading and utilization technologies. As many countries pursue carbon neutrality strategies, biomethane is expected to play an increasingly important role in decarbonizing transportation, industry, and natural gas networks. Although technologies such as membrane separation, water scrubbing, pressure swing adsorption, chemical absorption, and cryogenic upgrading have demonstrated promising performance, additional studies should focus on reducing upgrading costs, improving energy efficiency, minimizing methane losses, and integrating carbon capture, utilization, and storage (CCUS) technologies within biogas production systems (International Energy Agency [IEA], 2023).

Another significant research opportunity lies in the integration of biogas within circular bioeconomy systems. Existing literature primarily emphasizes renewable energy generation, whereas comparatively less attention has been devoted to nutrient recovery, biofertilizer commercialization, industrial symbiosis, biochar production, hydrogen generation, wastewater resource recovery, and integrated bio-refinery concepts. Future studies should evaluate how anaerobic digestion can be combined with complementary technologies to maximize resource recovery, reduce waste generation, and improve overall system efficiency within circular economy frameworks (Geissdoerfer et al., 2017; European Biogas Association, 2023).

From a socio-economic perspective, future research should investigate public acceptance, stakeholder participation, and community engagement in greater depth. Although social acceptance has been identified as an important determinant of renewable energy adoption, empirical evidence regarding behavioural factors, community perceptions, institutional trust, and participatory governance remains relatively limited. Comparative studies examining urban and rural communities, developed and developing countries, and different ownership models would improve understanding of the social factors influencing successful biogas implementation (Wüstenhagen et al., 2007; Bond & Templeton, 2011).

Policy and governance also warrant greater scholarly attention. Existing research consistently demonstrates that government incentives significantly influence biogas deployment; however, relatively few comparative studies evaluate the long-term effectiveness of different policy instruments across countries. Future investigations should examine feed-in tariffs, renewable portfolio standards, carbon pricing, investment subsidies, renewable gas certification, green financing mechanisms, and public-private partnerships to identify policy frameworks that best support sustainable biogas development under different institutional contexts (Scarlat et al., 2018; IEA, 2023).

Another promising direction involves regional and cross-country comparative studies. The current literature is heavily concentrated in Europe and China, while comparatively fewer investigations focus on Africa, Southeast Asia, Latin America, and small island developing states. These regions possess considerable biomass resources but differ substantially in terms of agricultural systems, institutional capacity, infrastructure, and socio-economic conditions. Comparative research across geographical contexts would improve understanding of region-specific barriers, opportunities, and policy interventions required to accelerate biogas adoption in emerging economies (Bond & Templeton, 2011).

Methodologically, future systematic reviews should employ more advanced bibliometric techniques, science mapping, network analysis, and meta-analysis to identify evolving research trends and interdisciplinary

collaborations within the rapidly expanding biogas literature. Combining bibliometric analysis with qualitative thematic synthesis would provide a more comprehensive understanding of knowledge development while identifying influential authors, institutions, countries, research clusters, and emerging research frontiers (Donthu et al., 2021).

Based on the findings of this review, future empirical research should also validate the integrated conceptual framework proposed in this study. Structural Equation Modelling (SEM), Partial Least Squares Structural Equation Modelling (PLS-SEM), system dynamics modelling, and multi-criteria decision-making approaches could be employed to examine the relationships among technical capability, economic viability, environmental sustainability, policy support, and social acceptance. Such empirical validation would strengthen theoretical understanding while providing practical guidance for policymakers, researchers, investors, and industry practitioners.

Overall, the future of biogas research lies in interdisciplinary collaboration that integrates engineering, environmental science, economics, agriculture, digital technologies, public policy, and social sciences. By addressing the identified research gaps and adopting holistic sustainability perspectives, future studies can significantly enhance the contribution of biogas technologies to renewable energy development, circular bioeconomy implementation, and the achievement of global Sustainable Development Goals (SDGs). Such research will be essential for supporting the global transition toward resilient, low-carbon, and resource-efficient energy systems.

CONCLUSION

The transition toward sustainable energy systems has intensified global interest in renewable energy technologies that simultaneously address climate change, waste management, and energy security. This systematic literature review examined the current state of knowledge on biogas energy by synthesizing evidence from previous studies on sustainability, anaerobic digestion technology, feedstock utilization, environmental impacts, economic and social perspectives, and emerging research directions. The review demonstrates that biogas has evolved into one of the most versatile renewable energy technologies because it converts biodegradable organic waste into valuable energy while contributing to environmental protection, resource recovery, and sustainable economic development.

The findings indicate that anaerobic digestion remains the cornerstone technology for biogas production. Significant advances have been achieved in reactor design, microbial process optimization, feedstock pretreatment, co-digestion strategies, and biomethane upgrading technologies. These technological developments have improved methane yields, operational stability, and overall energy conversion efficiency while expanding the range of suitable feedstocks, including livestock manure, agricultural residues, municipal organic waste, sewage sludge, food waste, and agro-industrial by-products. The increasing application of digital technologies such as artificial intelligence, machine learning, and real-time monitoring systems also presents new opportunities for optimizing anaerobic digestion processes and improving commercial-scale biogas production.

From an environmental perspective, the literature consistently confirms that biogas contributes significantly to greenhouse gas mitigation, sustainable waste management, pollution reduction, nutrient recycling, and circular economy implementation. By capturing methane emissions from organic waste and replacing fossil fuels with renewable energy, biogas supports national decarbonization strategies and global climate change mitigation efforts. Furthermore, digestate utilization enhances soil fertility and reduces dependence on synthetic fertilizers, strengthening the environmental sustainability of agricultural production systems. These multiple environmental benefits position biogas as an important component of integrated renewable energy and waste management strategies.

The review also demonstrates that the economic and social dimensions of biogas development are equally important for ensuring long-term sustainability. Economic feasibility is influenced by feedstock availability,

investment costs, government incentives, operational efficiency, market conditions, and diversified revenue streams derived from electricity generation, biomethane production, digestate utilization, and carbon markets. Social acceptance, stakeholder participation, institutional support, and public awareness are similarly critical determinants of successful technology adoption. Countries that have established supportive policy frameworks, financial incentives, and stable regulatory environments have generally experienced more rapid expansion of commercial biogas industries than countries with fragmented governance and limited institutional capacity.

Despite considerable progress, this review identifies several important research gaps. Existing studies remain fragmented across engineering, environmental science, economics, agriculture, and public policy, with relatively few investigations adopting integrated sustainability perspectives. The literature is also geographically concentrated in developed countries, while empirical evidence from developing regions remains comparatively limited despite substantial biomass availability and growing renewable energy demand. Furthermore, emerging areas such as artificial intelligence, digital process optimization, carbon capture integration, circular bioeconomy systems, biomethane commercialization, and advanced sustainability assessment require greater scholarly attention. Addressing these gaps will contribute to a more comprehensive understanding of the factors influencing successful biogas implementation across different geographical, institutional, and socio-economic contexts.

Based on the synthesis of the reviewed literature, this study proposes that sustainable biogas development should be viewed as the outcome of interactions among four interdependent dimensions: technical capability, environmental sustainability, economic viability, and social acceptance. Rather than functioning independently, these dimensions collectively determine the long-term performance, scalability, and resilience of biogas systems. Accordingly, future research and policy initiatives should adopt interdisciplinary approaches that integrate engineering innovation, environmental management, economic analysis, governance, and social sciences to maximize the contribution of biogas to sustainable development.

The findings of this review have important implications for researchers, policymakers, industry practitioners, and investors. For researchers, the review provides a comprehensive synthesis of existing knowledge and identifies promising directions for future investigation. For policymakers, the findings highlight the importance of stable regulatory frameworks, financial incentives, and integrated renewable energy policies that encourage biogas investment and commercialization. For industry stakeholders, the review emphasizes opportunities for technological innovation, digitalization, feedstock optimization, and circular business models that improve both environmental and economic performance. Collectively, these insights contribute to advancing evidence-based decision-making and supporting the broader transition toward low-carbon energy systems.

Although this review provides a comprehensive synthesis of the current literature, it is subject to several limitations. The analysis focuses primarily on peer-reviewed publications indexed in major academic databases and therefore may exclude relevant findings reported in government reports, technical documents, conference proceedings, and other forms of grey literature. In addition, the rapidly evolving nature of biogas research means that new technological developments and policy initiatives may emerge after the completion of this review. Future systematic reviews may therefore benefit from incorporating bibliometric analysis, meta-analysis, and longitudinal assessments to capture emerging research trends and technological advancements more comprehensively.

In conclusion, biogas represents a mature and increasingly important renewable energy technology capable of addressing multiple global sustainability challenges simultaneously. Its ability to transform organic waste into clean energy while reducing greenhouse gas emissions, improving waste management, supporting agricultural productivity, and strengthening circular economy practices makes it an essential component of future sustainable energy systems. Continued technological innovation, supportive public policies, interdisciplinary research, and international collaboration will be fundamental to unlocking the full potential of biogas and accelerating its contribution to achieving the United Nations Sustainable Development Goals and global net-zero emission targets.

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