
A Review of Integrative Approaches for Sustainable Biogas: Optimizing Production, Purification, and Environmental Mitigation

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Abstract: *This review paper comprehensively examines integrative approaches to optimizing sustainable biogas production, purification, and utilization, highlighting their roles in renewable energy transition and environmental impact mitigation. It systematically analyzes substrate selection and pretreatment methods, advances in anaerobic digestion technologies, and microbial management strategies to improve biogas yield and stability. Purification and upgrading processes, including contaminant removal techniques and emerging electrochemical and catalytic methods, are evaluated for their efficiency and techno-economic viability. The utilization of biogas in energy generation, fuel applications, and rural contexts is explored alongside the environmental implications, emphasizing nutrient recovery, digestate management, and greenhouse gas emission reduction. Further, policy frameworks, market adoption challenges, and innovative trends such as bio-electrochemical systems and IoT integration are discussed. This integrative review highlights progress and persisting challenges in enhancing biogas systems' sustainability, underscoring future research directions to foster broader adoption and technological advancement in the global energy landscape.*

Keywords: *sustainable biogas production, anaerobic digestion, biogas upgrading, renewable energy,*

1.0 Introduction

Biogas plays a crucial role in the transition to renewable energy and in mitigating climate change by offering a sustainable alternative to fossil fuels. As a renewable energy resource derived from the anaerobic digestion of organic wastes, biogas contributes to reducing greenhouse gas emissions by capturing methane that would otherwise be released into the atmosphere (Lamb, 2020; Uretski et al., 2023). Furthermore, biogas production aligns with circular economy principles by valorizing organic by-products and waste streams. The potential for biogas production is vast and diverse, originating from multiple types of substrates, including agricultural residues, municipal solid wastes, and algae.

Traditional substrates such as animal manure and food waste are well-established, while emerging feedstocks like algae hold promise for third-generation biofuels with higher productivity and CO₂ sequestration capabilities (Beschkov, 2022; Montuori et al., 2025; Mkhize, 2025). Algal biomass presents advantages such as rapid growth rates and the ability to integrate with wastewater treatment systems, although it also faces challenges in scalability and cost-effectiveness. Despite its promise, sustainable production and widespread utilization of biogas face significant challenges.

These include technological barriers in optimizing anaerobic digestion, purification and upgrading of biogas to biomethane standards, and economic and policy hurdles affecting adoption (Agdew et al., 2025; Kanda & Feiz, 2024). Additionally, differences in local resources, climatic conditions, and infrastructural constraints add complexity to biogas system deployment globally.

2.0 Objectives and Scope

This review synthesizes integrative strategies aimed at optimizing biogas yield, enhancing purification processes, and improving environmental benefits. It surveys current technological approaches, identifies key challenges, and presents recent advances and future research directions in biogas production and utilization. The scope encompasses substrate selection and pre-treatment, anaerobic digestion operational parameters, microbial community management, purification and upgrading techniques, diverse utilization pathways, environmental impacts including nutrient recycling and emissions reduction, and policy and market perspectives.

3.0 Biogas Production Optimization

3.1 Substrate Selection and Preparation

The chemical composition of feedstocks markedly influences biogas potential; substrates rich in biodegradable organic matter, such as carbohydrates and proteins, tend to yield higher methane volumes (Dandikas, V., 2018). Co-digestion of multiple substrates, for example, combining animal manure with agricultural residues or industrial by-products, enhances biochemical methane potential by balancing nutrient availability and improving digestion stability (Nett et al., 2024; Suanggana et al., 2022). For instance, co-digesting cattle manure with winemaking waste or sugarcane residues has shown increased gas yields and energy recovery. Lignocellulosic biomass constitutes a large portion of agricultural residues but is recalcitrant due to complex lignin matrices, limiting microbial accessibility and biogas yield. Pretreatment methods such as thermal, biological, and enzymatic processes have demonstrated efficacy in increasing biodegradability and biogas production (Dahahda, 2015; Khalid, 2019; Mishra, 2019).

Combining alkaline pretreatment with nanomaterial additives like magnetite nanoparticles further enhances yield, simultaneously improving microbial kinetics and substrate digestibility.

3.2 Anaerobic Digestion Technologies and Operational Parameters

Anaerobic digestion configurations include liquid anaerobic digestion (L-AD) and solid-state anaerobic digestion (SS-AD), each with distinctive traits influencing biogas production dynamics. Nugraha et al. (2020) compared these modes for water hyacinth substrates, finding L-AD to result in higher biogas yield at optimized total solids and C/N ratios. Proper adjustment of parameters such as temperature, mixing, hydraulic retention time (HRT), and reactor pressure are essential for process optimization.

Makamure et al. (2024) demonstrated that integrating solar heating into fixed dome digesters increased temperature control, leading to a 33% rise in cumulative biogas volume and improved methane content. Additives like biochar derived from biogas waste, zero-valent iron (nZVI), and magnetic nanoparticles stably augment anaerobic digestion microbial activity and pollutant removal, resulting in higher gas volumes and reduced inhibition (Limbu & Subba, 2024; Dahahda, 2015). For example, biochar pyrolyzed at elevated temperatures combined with nZVI significantly enhanced COD removal and sulfide control in pig farm wastewater treatment systems.

3.3 Microbial Community and Process Stability

The microbial consortia responsible for anaerobic digestion comprise hydrolytic, acidogenic, acetogenic, and methanogenic populations. Stable biogas production hinges on balanced metabolic interactions and resilience to inhibitors like hydrogen sulfide (H₂S) and ammonia (Kanellos, 2025). Microbial additives or biogas slurry recycling can modulate community structure to favor methanogenesis, offset substrate inhibition, and enhance reactor stability, as observed in Evogen microbial additive applications increasing hydrolytic and methanogenic populations (Sfetsas et al., 2023) and sludge addition strategies that accelerate biogas formation (Kurniasari, 2018).

4.0 Biogas Purification And Upgrading

4.1 Removal of Contaminants

Raw biogas contains undesirable gases such as H₂S, CO₂, ammonia, and siloxanes that reduce calorific value and cause corrosion. Multiple removal technologies have been developed. Biofiltration leveraging activated sludge cultures or natural materials like zeolite, activated carbon from agricultural residues, red rock, and volcanic ash demonstrate significant H₂S adsorption capacity and regeneration potential (Khangamage et al., 2021; Thandeka N. K., 2024).

Carbon dioxide removal, essential to increase methane content, can be achieved by water scrubbing, which dissolves CO₂ more readily than methane, adsorption onto various adsorbents including biochar and montmorillonite clay, membrane gas separation technologies, and biological methods employing microalgal cultivation for concurrent nutrient and CO₂ removal (Sidabutar et al., 2023; Mulya Gantina et al., 2020) Water scrubber studies reveal efficiencies exceeding 99% CO₂ removal at optimized pressure and flow rates.

4.2 Advanced Upgrading Technologies

Emerging ex-situ and in-situ upgrading methodologies encompass solid oxide electrolysis cells (SOEC) for co-electrolysis of biogas components, catalytic conversion, and biological hydrogen addition. These approaches aim to enrich methane concentration to biomethane standards suitable for grid injection or vehicle fuel (Lamb, 2020; Hansen et al., 2013). Comparative techno-economic assessments emphasize the cost sensitivity of hydrogen input in biological upgrading, with scaling and feedstock costs being critical factors (Lawson et al., 2021; Hartvigsen et al., 2020).

4.3 Modeling and Simulation

Simulation models of biogas plants capture anaerobic digestion kinetics and upgrading dynamics to optimize plant operation and predict outputs. Zepter et al. (2021) demonstrated accurate internal process simulation in a 3 MW Danish biogas plant, while Heiker et al. (2021)

systematically reviewed modeling approaches from detailed biochemical to energy system models, highlighting the need for integrated, dynamic optimization frameworks.

5.0 Biogas Utilization

5.1 Energy Generation

Biogas is utilized for electricity, heat, and combined heat and power (CHP) generation. Cogeneration plants fueled by animal waste biogas improve energy self-sufficiency on livestock farms, with Manganelli (2013) showing economic advantages in Italy. Poly-generation concepts expand utilization efficiency by integrating biogas-derived electricity, heat, and high-value chemicals (Welch, 2019). At smaller scales, optimized agitators in digesters reduce energy consumption while maintaining productivity (Lemmer et al., 2013). Solid oxide fuel cells (SOFC) represent an advanced technology that converts biogas into electricity with higher efficiencies and potential carbon capture integration, as evaluated by Yu et al. (2023) and Engelhardt et al. (2021).

5.2 Fuel and Combustion Optimization

The combustion characteristics of biogas depend on methane content and the presence of inert gases. Chen et al. (2021) investigated thermal characteristics of biogas-hydrogen blends, showing enhanced flame stability and reduced pollutant emissions relative to pure biogas. Oxygen enrichment also improves combustion efficiency (Kacua et al., 2011). Upgraded biomethane facilitates grid injection and vehicle fuel applications, often employing membrane or scrubbing technologies for purification (Mertins & Wawer, 2022).

5.3 Domestic and Rural Applications

Household-scale digesters adapted to local contexts serve as key solutions for decentralized energy generation. Rajendran et al. (2012) reviewed small-scale digesters, emphasizing cost-effectiveness and ease of use. Urban and rural installations with optimized burner designs

enhance thermal efficiency and reduce fuel consumption (Montuori et al., 2024; Sari et al., 2023).

6.0 Environmental Impact And Sustainability Assessment

6.1 Nutrient Recovery and Digestate Management

Digestate from anaerobic digestion is nutrient-rich and can substitute chemical fertilizers. Aso et al. (2022) quantified global fertilizer cost savings from biogas coproduct reuse. Digestate treatment technologies, including membrane-based nutrient recovery systems, improve resource efficiency and support sustainable agriculture (Khan et al., 2022).

6.2 Greenhouse Gas Emission Reduction

Biogas adoption leads to significant reductions in methane and CO₂ emissions by substituting fossil fuels and avoiding methane release from decomposing wastes (Hoang & Kato, 2021). Methane slip during upgrading is small but environmentally consequential; mitigation technologies such as regenerative thermal oxidizers have been applied (Kvist & Aryal, 2018; Uretski et al., 2023).

6.3 Life Cycle and Techno-Economic Assessments

Life cycle assessments provide insights into energy balances and environmental benefits, indicating that biogas systems can achieve positive net renewable energy and greenhouse gas reductions after operational thresholds (Lindfors et al., 2023; Makaka et al., 2022). Economic analyses show that mid-sized biogas plants achieve profitability over reasonable payback periods, although policy and market conditions strongly influence investment viability (Larsson et al., 2025).

7.0 Policy, Market, And Socio-Economic Perspectives

7.1 Policy and Regulatory Frameworks

Supportive policies are essential for biogas uptake, including feed-in tariffs, renewable energy mandates, and environmental regulation frameworks that incentivize biogas production and utilization (Tsai, 2018; Mishra, 2019; Vetter, 2024).

7.2 Market Development and Adoption Barriers

Barriers to biogas market development span technological knowledge gaps, financial constraints, regulations, and social acceptance (Kanda & Feiz, 2024; Aso et al., 2022; Ritonga et al., 2025). Cooperative business models and producer networks offer pathways to overcome financing and technical hurdles.

8.0 Innovation And Emerging Trends In Biogas Systems

Emerging trends integrate bioelectrochemical technologies, microalgae cultivation for CO₂ removal and nutrient recycling, and IoT-enabled automation systems to advance biogas production efficiency and monitoring (Kanellos, 2025; Mertins & Wawer, 2022; Rohmah, 2019). In the global energy transition context, biogas remains competitive against emerging fuels like hydrogen due to its cost-effectiveness and mature technology base (Constantin, 2024; Vetter, 2024; Heiker et al., 2021).

9.0 Conclusion

This review underscores that optimizing sustainable biogas production depends on an integrated approach encompassing appropriate substrate selection, advanced pretreatment methods, and optimized anaerobic digestion, including effective microbial management. Significant progress has been made in biogas purification and upgrading, particularly through emerging electrochemical and catalytic technologies that enhance methane recovery and contaminant removal. Biogas utilization across energy generation, fuel applications, and rural household systems supports energy access and socio-economic development. Environmental

benefits are strengthened through nutrient recovery, digestate valorization, and substantial greenhouse gas emission reductions. Nevertheless, economic viability, process stability, and market adoption remain key challenges, underscoring the need for supportive policies, continued innovation, and future research focused on scalable, cost-effective biogas systems.

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