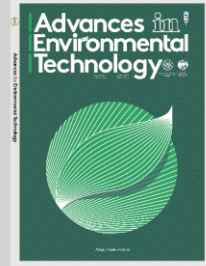




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Advances in biogas production technologies: Feedstock utilization, process optimization, and sustainable energy applications

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ABSTRACT

Biogas production through anaerobic digestion (AD) is an important renewable-energy pathway that supports organic-waste management, resource recovery, and decarbonization of energy systems. However, its performance varies with feedstock characteristics, process conditions, technology configuration, infrastructure, and local economic and policy conditions. This review critically synthesizes advances in biogas production technologies, emphasizing feedstock utilization, process optimization, anaerobic digestion configurations, biogas upgrading, sustainable energy applications, environmental performance, techno-economic feasibility, and emerging technological pathways. A structured literature search was conducted using Scopus, Web of Science, and Google Scholar, resulting in a final evidence base of 174 references selected through predefined eligibility and data-extraction criteria. The review shows that co-digestion, pretreatment, temperature-phased digestion, reactor optimization, and advanced process monitoring can improve methane production and operational stability, although reported performance is strongly dependent on feedstock composition and experimental conditions. The analysis further demonstrates that methane leakage, digestate management, energy requirements, and system boundaries can substantially influence the environmental benefits of AD. Economic viability is similarly context-dependent, influenced by plant scale, feedstock logistics, financing conditions, energy markets, infrastructure, and policy support. Advanced upgrading, digital monitoring, hydrogen-assisted methanation, nutrient recovery, biochar-assisted digestion, and bioelectrochemical approaches offer further opportunities, but their technological readiness and commercialization prospects differ considerably. The review identifies persistent gaps in scale-up validation, methane-loss measurement, standardized techno-economic and life-cycle assessment, feedstock variability, and deployment in developing regions. Future progress will depend on integrated systems that combine reliable methane production

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with methane-loss minimization, resource recovery, digital process control, economic viability, and verified life-cycle environmental performance.

1. Introduction

The global demand for renewable energy has intensified in recent decades in response to climate change, environmental degradation, and energy insecurity. Among renewable energy carriers, biogas derived from AD offers unique advantages: it simultaneously provides decentralized energy, supports waste management, and reduces greenhouse gas (GHG) emissions. Biogas systems can valorize diverse organic feedstocks—including agricultural residues, animal manure, municipal solid waste, and industrial by-products—into methane-rich gas suitable for cooking, heating, electricity, or upgrading to biomethane for grid injection [1,2]. In addition, digestate from the AD process can be used as a nutrient-rich biofertilizer, further contributing to circular economy objectives [3].

Globally, agricultural residues and animal manure represent the most significant untapped feedstock potential for biogas production, especially in developing economies where agriculture dominates the economy [4]. The International Energy Agency (IEA) has identified crop residues and manure as the largest sustainable sources of biogas feedstock, with strong potential for deployment in rural and peri-urban contexts [4,5]. Country-level assessments in West Africa similarly highlight the abundant availability of agricultural residues and municipal waste streams, though logistical and infrastructural limitations often constrain full utilization [6,7].

Despite its promise, the efficiency of anaerobic digestion is often hampered by factors such as feedstock recalcitrance, inhibitory compounds, and operational instability [8,9]. Recent research emphasizes the importance of pretreatment strategies (mechanical, thermal, chemical, and biological) to improve hydrolysis of lignocellulosic materials, thereby enhancing methane yields [10]. In addition, co-digestion of multiple substrates, such as food waste with livestock manure, has been shown to balance nutrient composition, improve microbial activity, and mitigate process inhibition [11]. Decision-support approaches such as the

Analytic Hierarchy Process have also been applied to optimize feedstock selection for sustainable small-scale systems [12].

Advances in understanding and managing the microbial ecology of anaerobic digesters are equally important. Studies using molecular and metagenomic approaches reveal how temperature regimes, feedstock variability, and process upsets shape microbial community dynamics, which in turn govern reactor stability and methane productivity [13]. Coupled with digital monitoring tools and machine learning-based predictive models, these insights are paving the way toward “smart” AD systems with higher robustness and adaptive performance.

Nonetheless, challenges remain in terms of scalability, cost, and environmental trade-offs. Variability in feedstock supply chains, energy intensity of pretreatment processes, and the management of residual digestate continue to affect both economic viability and environmental performance [14,15]. Moreover, policy and regulatory frameworks often lag behind technological advances, especially in developing regions where feedstock is abundant but infrastructure investment remains limited [16,17]. Recent reviews have substantially advanced understanding of individual components of anaerobic digestion and biogas systems. For example, recent studies have reviewed technological breakthroughs in anaerobic digestion of organic biowaste, strategies for improving digestion performance, anaerobic co-digestion, and the broader production, properties, applications, and challenges of biogas [3,9,18–20]. Other studies have focused more specifically on pretreatment of lignocellulosic substrates, dry anaerobic digestion, biogas upgrading, digestate valorization, and emerging bioenergy technologies [21–26]. Membrane-based separation has also been investigated as an important pathway for separating and purifying biofuels, with implications for the development of efficient gas-upgrading systems [27]. These contributions provide valuable foundations for understanding individual technological pathways; however, the

literature remains fragmented across feedstock characteristics, biochemical and operational optimization, reactor configurations, downstream upgrading, environmental performance, economics, and end-use applications.

A further limitation is that improvements reported for individual technologies are not always directly transferable across feedstocks or operating conditions. Methane production is strongly influenced by substrate composition, biodegradability, inoculum characteristics, temperature, organic loading rate, hydraulic retention time, reactor configuration, pretreatment intensity, and inhibition mechanisms. Recent evidence indicates, for example, that the response of methane yield to pretreatment depends strongly on substrate chemical composition [28]. Consequently, reporting methane-yield improvements without considering the experimental context can obscure the reasons for apparently conflicting results. A critical review is therefore needed that moves beyond listing technological advances and instead examines why performance varies among studies, under which conditions an intervention is effective, and what constraints limit its scale-up and practical deployment.

In addition, the transition from laboratory-scale process improvement to sustainable energy application involves several interconnected considerations that are frequently addressed separately. These include biomethane upgrading and utilization, fugitive methane emissions, life-cycle environmental performance, techno-economic feasibility, digestate valorization, policy and infrastructure, and differences in technological maturity between developed and developing countries. The emergence of digital monitoring, artificial intelligence, green-hydrogen integration, and power-to-gas pathways further increases the need for an integrated assessment of technological readiness, scalability, environmental implications, and commercialization prospects. Thus, the principal gap addressed by this review is not the absence of literature on individual biogas technologies, but the limited integration of process-level advances with system-level environmental, economic, and deployment considerations within a single critical framework.

Accordingly, this review provides a critical and cross-scale synthesis of advances in biogas production technologies, linking feedstock characteristics and biochemical mechanisms to process optimization, reactor performance, gas upgrading, end-use applications, environmental impacts, and economic feasibility. Particular emphasis is placed on (i) explaining the causes of variation in reported methane performance across feedstocks and operating conditions; (ii) critically comparing pretreatment, co-digestion, reactor, and process-control strategies rather than merely describing their reported benefits; (iii) examining the implications of biogas upgrading, methane leakage, digestate management, and life-cycle emissions for overall environmental performance; (iv) comparing technological maturity, economic conditions and implementation barriers in developed and developing countries; and (v) assessing emerging pathways, including digitalization, artificial intelligence, green-hydrogen integration and power-to-gas, in terms of technological readiness, limitations, and commercialization potential. This integrated perspective is intended to identify the most important technological and systemic research gaps that must be addressed for biogas to contribute more effectively to sustainable energy transitions.

2. Literature Search Strategy and Methodology

A structured literature search and synthesis framework was adopted to identify, evaluate, and integrate evidence on recent advances in biogas production technologies. The methodology was designed to provide a transparent basis for examining developments in feedstock utilization, anaerobic digestion and process optimization, biogas upgrading, sustainable energy applications, and emerging technological pathways. The search and selection process comprised database identification and literature retrieval, application of predefined search terms and eligibility criteria, extraction of relevant technical and performance information, and thematic synthesis of the selected evidence. Particular attention was given to quantitative performance indicators and the operational conditions under which reported results were obtained, allowing technological

advances and their limitations to be critically compared across studies.

2.1. Literature Search and Database Selection

A structured literature search and screening protocol was developed to provide a transparent and reproducible basis for synthesizing recent advances in biogas production technologies. Literature was identified from three major electronic databases: Scopus, Web of Science, and Google Scholar. Scopus and Web of Science were used as the principal bibliographic databases because of their broad coverage of peer-reviewed scientific literature, while Google Scholar was used as a supplementary source to identify additional relevant publications, highly cited foundational studies, and literature that may not have been retrieved through the primary databases.

The search focused primarily on literature published between 2015 and 2026, reflecting the objective of capturing contemporary developments in anaerobic digestion, biogas upgrading, sustainable energy applications, and emerging technologies. Highly cited earlier publications were retained where they provided important foundational knowledge on anaerobic digestion mechanisms, inhibition, feedstock characteristics, reactor technologies, or other concepts necessary for interpreting recent advances. The search was complemented by examination of reference lists of highly relevant publications to identify additional studies directly related to the objectives of the review.

2.2. Search Strategy and Keywords

The search strategy combined Boolean operators with keywords representing the principal technological and sustainability dimensions of biogas systems. The primary search string was: ("anaerobic digestion" OR "biogas" OR "biomethane") AND ("pretreatment" OR "co-digestion" OR "process optimization") AND ("techno-economic analysis" OR "life cycle assessment" OR "circular economy").

Additional keyword combinations were used to capture topics not fully represented by the primary search string, including biogas upgrading, methane leakage, anaerobic digestion inhibition, reactor configuration, digestate valorization, biomethane, hydrogen integration, power-to-gas,

artificial intelligence, digital monitoring, and renewable energy applications. Searches were conducted using combinations of these terms and their relevant synonyms to improve retrieval of studies addressing specific technological pathways and emerging applications.

2.3. Eligibility and Study Selection

Publications were considered eligible when they were directly relevant to biogas production, anaerobic digestion, biogas upgrading, biomethane utilization, environmental performance, techno-economic assessment, or emerging technologies associated with sustainable biogas systems. Priority was given to peer-reviewed journal articles, while relevant book chapters and authoritative reports from recognized institutions, including the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), were retained where they provided important technical, economic, policy, or resource-potential information.

Inclusion criteria required studies to provide sufficient methodological or technical information to support interpretation and comparison of their findings. For studies reporting experimental or process-performance data, particular attention was given to quantitative indicators such as biogas yield, methane yield, methane concentration, volatile-solids reduction, organic loading rate, hydraulic retention time, temperature, pH, reactor configuration, and pretreatment conditions. Studies addressing environmental or economic performance were included when they reported relevant indicators such as greenhouse-gas emissions, life-cycle impacts, capital or operating costs, levelized costs, payback period, net present value, or other clearly defined economic metrics.

Studies were excluded when they lacked sufficient methodological information, were not directly relevant to the objectives of the review, duplicated information already represented by another publication, or originated from sources considered unreliable or predatory. Laboratory-scale studies were not automatically excluded; they were retained when they provided meaningful information on biochemical mechanisms, inhibition, pretreatment, process optimization, microbial interactions, or technologies with potential implications for scale-up.

The final literature base comprised 174 references, including peer-reviewed research articles, review articles, book chapters, and authoritative institutional sources.

2.4. Data Extraction and Evidence Synthesis

For the selected literature, information was extracted according to the specific objective of each thematic section. For studies reporting methane-production performance, the extracted variables included feedstock type and composition, digestion mode, temperature regime, inoculum characteristics, pretreatment status, reactor configuration, hydraulic retention time, organic loading rate, volatile-solids basis, methane yield, methane concentration, and relevant experimental conditions. For studies addressing upgrading and energy applications, information on methane recovery, product purity, energy requirements, technology configuration, and application pathway was considered. Economic and environmental studies were evaluated according to the system boundary, functional unit, major economic assumptions, greenhouse-gas indicators, and principal sources of uncertainty where these were reported.

Because methane yields reported in the literature are strongly dependent on experimental and reporting conditions, values from different studies were interpreted in their original methodological context rather than treated as universally equivalent. Particular attention was given to differences between biochemical methane potential (BMP) tests and continuous or semi-continuous digestion, digestion temperature, retention time, substrate basis, pretreatment, and gas-volume reporting conditions. Where studies used different experimental bases or reporting units, direct numerical comparison was avoided unless sufficient information was available to establish comparability. Consequently, reported methane-yield ranges are presented primarily as indicators of the performance envelope of different feedstocks and technologies rather than as standardized meta-analytic estimates.

2.5. Critical Synthesis

The selected literature was synthesized thematically rather than solely chronologically. The analysis compared technological interventions

according to their reported benefits, operating requirements, limitations, scalability, environmental implications, and economic considerations. Particular emphasis was placed on explaining differences among studies in terms of feedstock composition, biodegradability, reactor configuration, operating conditions, pretreatment intensity, inhibition, and system boundaries. This approach was used to distinguish improvements that are consistently reported across different studies from those that are strongly dependent on specific experimental or deployment conditions. The review therefore combines quantitative evidence reported in the literature with qualitative comparison of technological maturity, implementation barriers, environmental trade-offs, and commercialization prospects. This approach enables the review to move beyond a descriptive catalogue of technologies and to identify the conditions under which particular biogas-production and utilization pathways are most technically, environmentally, and economically appropriate.

3. Feedstocks for Biogas Production

The performance of anaerobic digestion and the quality of biogas produced are strongly influenced by the characteristics of the feedstock. Substrate choice determines not only methane yield but also process stability, microbial community dynamics, and the economic viability of the plant. An ideal feedstock should be abundant, biodegradable, and balanced in nutrients, but in practice, substrates vary widely in chemical composition, seasonal availability, and logistical costs [29,30].

3.1. Classification of Feedstocks

Feedstocks for AD are broadly categorized into: (i) animal manure and slurries—nutrient-rich but typically low in organic loading potential [31]; (ii) municipal and industrial organic wastes – including sewage sludge, food waste, and agro-industrial residues, which are highly degradable but often heterogeneous and contaminated [32]; (iii) agricultural residues and lignocellulosic biomass – abundant but recalcitrant due to their lignin-cellulose matrix [33]. Agricultural and lignocellulosic residues can also serve as feedstocks for thermochemical and other bioenergy

conversion pathways, illustrating the importance of selecting conversion technologies according to feedstock characteristics and desired energy products. For example, torrefaction can induce morphological and chemical transformations in agro-wastes and facilitate their conversion into porous carbon-based biofuels [34]. Although torrefaction is not an anaerobic-digestion process, such pathways are relevant to integrated biomass valorization because they provide alternative routes for recalcitrant residues that may be less suitable for direct biological conversion. Consequently, feedstock selection should consider not only theoretical methane potential but also biodegradability, pretreatment requirements, competing valorization pathways, energy inputs, and the environmental and economic performance of the overall conversion system; (iv) energy crops – high-yielding dedicated crops such as maize silage, offering stable supply but raising food–fuel competition concerns [35]; and (v) co-digestion mixtures – blending substrates to achieve synergistic effects in nutrient balance and process stability [36].

3.2. Critical Feedstock Characteristics

Several feedstock properties govern AD performance:

(i) **Organic composition (TS/VS):** Organic composition, specifically measured through Total Solids (TS) and Volatile Solids (VS), is a critical parameter that determines the biogas and methane yield per unit mass of feedstock. VS represents the organic fraction of the total solids that can be converted into biogas, while higher TS indicates more solid matter, which, up to a certain threshold (15%–20%), can increase potential, but can also cause inhibition at higher concentrations (30%–35% TS) [21].

(ii) **C:N ratio:** An optimal Carbon-to-Nitrogen (C:N) ratio of 20:1 to 30:1 ensures that microorganisms have sufficient carbon for energy and enough nitrogen for protein synthesis, effectively preventing ammonia toxicity from excess nitrogen and stunted decomposition from nitrogen deficiency [37].

(iii) **Lignin and fiber content:** High fractions of lignin and fiber (specifically crystalline cellulose and hemicellulose) act as a structural barrier in plant biomass, significantly reducing enzymatic

hydrolysis rates and necessitating pretreatment. Lignin restricts access of enzymes to cellulose, and both lignin and hemicellulose prevent efficient degradation, necessitating methods that break down this complex, rigid matrix [38].

(iv) **Contaminants and inhibitors:** Heavy metals (e.g., Cd, Cr, Pb, Hg, As), salts, and siloxanes are significant contaminants that inhibit microbial activity and damage downstream equipment. These contaminants, often arising from industrial wastewater and waste, disrupt essential cellular enzymes and metabolic functions. Siloxanes in biogas cause abrasive white silica deposits in engines, while salts and heavy metals reduce microbial biomass and performance in anaerobic digestion [39]. For example, food waste and sewage sludge offer rapid biodegradability but often contain excess nitrogen, leading to ammonia toxicity [40]. Conversely, crop residues such as rice straw or corn stover are abundant but lignin-rich, which constrains methane yield unless pretreated [18].

3.3. Feedstock-Specific Opportunities and Challenges

(i) Animal manure ensures a steady supply and enhances buffering capacity but produces modest methane yields. Its co-digestion with carbon-rich residues often improves performance by providing necessary nutrients and balancing carbon-to-nitrogen ratios [19].

(ii) Municipal organic waste is attractive in urban settings for waste management and energy recovery, but heterogeneity and contamination complicate process control [20].

Agricultural residues hold vast potential, particularly in developing economies where they are underutilized. Their recalcitrance, however, necessitates pretreatment innovations [2,41]. These innovations can include physical, chemical, or biological methods to break down the tough structure of agricultural residues and make them more accessible to microbial degradation. Agricultural and lignocellulosic residues can also serve as feedstocks for alternative biomass-conversion pathways, illustrating the importance of matching conversion technology to feedstock characteristics and desired energy products. For example, torrefaction induces morphological and chemical transformations in agro-wastes and can

facilitate their conversion into porous carbon-based biofuels [34].

Although torrefaction is distinct from anaerobic digestion, such thermochemical pathways are relevant to integrated biomass valorization because they provide alternative routes for recalcitrant residues that may require substantial pretreatment for biological conversion. Consequently, feedstock selection should consider not only theoretical methane potential but also biodegradability, pretreatment requirements, competing valorization pathways, energy inputs, and the environmental and economic performance of the overall conversion route.

Energy crops such as maize silage have been shown to have a high energy and CO₂ balance for biogas production, making them suitable for anaerobic digestion. However, sustainability concerns regarding land use competition and environmental impacts need to be considered for their long-term role in energy production [42,43].

(iii) Co-digestion strategies increasingly dominate research, as they address nutrient imbalances, mitigate inhibitors, and enhance biogas yield while supporting circular economy models [18].

3.4. Sustainability and Practical Considerations

Beyond biochemical suitability, feedstock viability depends on logistical and environmental dimensions. Transportation costs, seasonal fluctuations, competing uses (e.g., fodder, soil amendment), and indirect land-use impacts all shape the feasibility of biogas systems. Recent IEA assessments emphasize that over 80% of global biogas potential lies in agricultural residues and organic wastes in developing regions, but infrastructural and policy barriers prevent large-scale exploitation [22]. Addressing these systemic challenges is therefore as important as optimizing digestion performance. Table 1 shows the reported methane yields and operating characteristics of

selected biogas feedstocks, while Figure 1 provides a visual comparison of the mean of reported methane yields for selected anaerobic digestion feedstocks.

The reported methane yields demonstrate substantial variability both among and within feedstock categories. Such variation should not be interpreted solely as an intrinsic difference in substrate quality because the reported values were obtained under different experimental and operational conditions.

For example, food-waste studies may distinguish between theoretical methane potential and actual methane production based on VS entering or leaving the digester, whereas municipal sewage sludge yields vary considerably with sludge type, with primary sludge generally exhibiting higher methane potential than waste-activated sludge.

Similarly, methane production from animal manure varies among livestock types because of differences in organic composition and biodegradability. For lignocellulosic feedstocks, particle-size reduction and other pretreatment strategies can substantially increase substrate accessibility and methane production, as demonstrated for rice and wheat straw. These differences highlight the importance of considering the yield basis, digestion mode, temperature, pretreatment, and reactor conditions when comparing methane-yield data across studies.

4. Process Optimization in Biogas Production

The efficiency and stability of biogas systems depend not only on the feedstock used but also on the operational parameters and technological interventions that govern microbial activity. Process optimization ensures maximum methane yields, reduced retention times, and improved system resilience against inhibition. The following subsections review key optimization strategies.

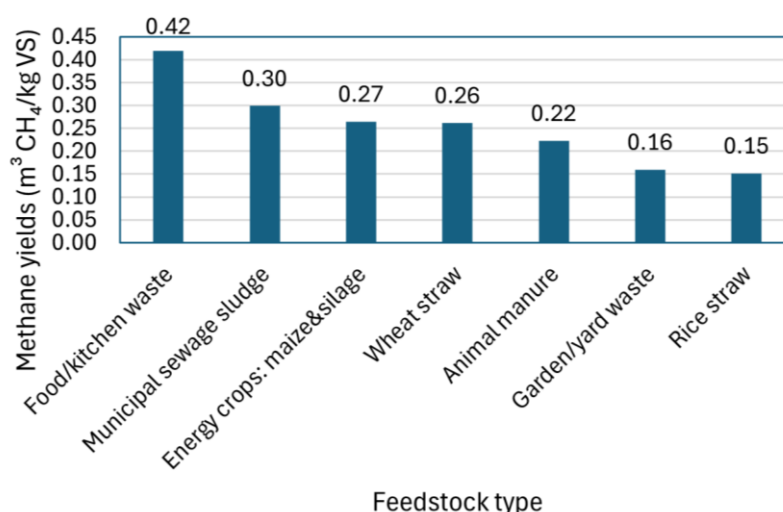


Fig. 1. Mean of reported methane yields for selected anaerobic digestion feedstocks. Source: Authors' analysis based on the studies cited in Table 1. (**Note:** Values in Figure 1 represent arithmetic means of the reported methane-yield values selected for each feedstock category in Table 1 and are presented for comparative visualization. They should not be interpreted as statistically pooled literature averages because the underlying studies differ in feedstock composition, digestion conditions, pretreatment, reactor configuration, and experimental methodology.)

Table 1. Reported methane yields and operating characteristics of selected biogas feedstocks.

Feedstock type	Digestion mode	Operating temperature	Pretreatment status	Reported methane yield	Sources
Food/kitchen waste	Full-scale biogasification	Facility-specific	Raw food waste/leachate	0.36 Sm ³ CH ₄ /kg VS-in (actual); 0.48 Sm ³ /kg VS-rem (actual); 0.52–0.53 Sm ³ /kg VS (theoretical)	[44]
Municipal sewage sludge	Anaerobic digestion	Mesophilic/thermophilic	Study-dependent	0.425 Nm ³ /kg VS (primary sludge); 0.296 Nm ³ /kg VS (mixed sludge); 0.176 Nm ³ /kg VS (waste-activated sludge)	[45]
Animal manure	Batch BMP	37 °C	Untreated	0.444 (piglet); 0.222 (cattle); 0.178 (sow); 0.173 (chicken); 0.169 (goat); 0.153 m ³ CH ₄ /kg VS (buffalo)	[46]
Energy crops (maize/maize silage)	Batch BMP	Experimental conditions	Fresh/ensiled	0.196–0.335 m ³ CH ₄ /kg VS (silage maize)	[47]
Rice straw	Batch AD	Experimental conditions	Particle-size reduction	0.107–0.197 m ³ CH ₄ /kg VS	[48]
Wheat straw	Batch BMP	37 °C	Untreated/mechanical pretreatment	0.237 ± 0.016 m ³ CH ₄ /kg VS untreated; up to 0.287 ± 0.024 m ³ CH ₄ /kg VS after roll milling	[49]
Garden/yard waste	Batch BMP	Study-dependent	Untreated/co-digestion	0.160 m ³ CH ₄ /kg VS	[50]
Human feces	Batch AD/BMP	Experimental conditions	Fresh/urine-diverted	0.38–0.40 m ³ CH ₄ /kg fresh matter; mean 0.393 m ³ /kg	[51]

Note: AD = anaerobic digestion; BMP = biochemical methane potential; VS = volatile solids. Reported methane yields are presented according to the basis and conditions specified in the cited studies and are not necessarily directly comparable because of differences in feedstock composition, digestion mode, operating temperature, pretreatment, reactor configuration, inoculum, retention time,

and gas-volume reporting conditions. Gas-volume conditions were retained as reported in the original studies (e.g., Nm³ or Sm³ where specified); values were not converted to a common standard condition when the original reporting basis was unclear.

4.1. Temperature Regimes

Anaerobic digestion can be operated under psychrophilic (10–20 °C), mesophilic (30–40 °C), or thermophilic (50–60 °C) conditions. Thermophilic digestion typically enhances hydrolysis and pathogen removal, while mesophilic processes are more stable and energy-efficient [18]. Recent studies highlight hybrid or temperature-phased anaerobic digestion (TPAD) as a promising approach, where the initial hydrolysis occurs under thermophilic conditions followed by mesophilic methanogenesis, improving methane yields by up to 25% [22].

4.2. pH and Alkalinity Control

Maintaining pH between 6.8 and 7.4 is critical for methanogenic activity as it affects the composition and production of biogas. Lower pH levels can inhibit methanogens, while higher pH levels can lead to slower degradation of acetate. There is a positive correlation between methane content in biogas and pH of the reactor [52,53]. Volatile fatty acids (VFAs) accumulation often leads to pH drops, inhibiting methanogenesis [54]. Buffering agents such as sodium bicarbonate or co-digestion with alkaline feedstocks (e.g., manure) are common strategies to stabilize pH [55]. Novel biochar amendments have also shown promise in enhancing buffering capacity and microbial stability [28].

4.3. Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT)

Balancing OLR and HRT is crucial to avoid process overload and washout of slow-growing methanogens. For mesophilic digesters, an OLR of 2–4 kg VS/m³/day and HRT of 20–30 days is generally optimal [20]. Exceeding these limits can result in a decrease in methane production efficiency and even system failure. It is important to carefully monitor and adjust the OLR and HRT to maintain a stable and productive anaerobic digestion process. Additionally, increasing the HRT can help to provide more time for microorganisms to break down organic matter, leading to higher methane yields. Advanced monitoring using real-

time sensors and machine learning has been applied to optimize OLR dynamically, minimizing failure risks while maximizing productivity [18]. Overloading can lead to a decrease in biogas production, but it is not a reliable early warning indicator [56]. Methane production rate can be used as an online indicator to control the process and detect imbalance [57]. Manure digesters with retention times of several days can experience stress conditions during overload situations. VFA levels can indicate process imbalance effectively, while biogas production may not reflect stress conditions accurately [58]. Operating conditions and reactor configuration can impact the efficiency of biogas plants, with high ammonia concentrations leading to lost methane production [59].

4.4. Co-digestion Strategies

Mono-digestion of certain substrates often leads to nutrient imbalance (e.g., high C/N ratios in crop residues). Co-digestion combines complementary feedstocks, improving process stability and methane yields [60]. For instance, co-digesting cattle manure (low C/N) with maize silage (high C/N) has been shown to increase methane production by 20–40% [61,62]. Similarly, food waste and sewage sludge co-digestion enhances biogas yields while improving waste management efficiency [63,64].

4.5. Pretreatment Technologies

Pretreatment improves substrate biodegradability, particularly for lignocellulosic biomass [65]. Common approaches for pretreatment of lignocellulosic biomass include mechanical methods like milling and extrusion, thermal methods such as steam explosion and microwave irradiation, chemical methods like acid or alkali treatment, and biological methods involving bacterial and fungal microorganisms [66]. These pretreatment technologies break down the complex structure of lignocellulosic biomass, making it more accessible to microbes during the digestion process [67]. This ultimately leads to higher biogas yields and more efficient conversion of organic waste into renewable energy sources.

Steam explosion, for example, has been reported to increase methane yields from straw by over 100% [22,68]. Emerging approaches include nanomaterials and combined chemo-thermo-biological pretreatments that accelerate hydrolysis and improve overall biogas production [28].

4.6. Inhibition Control

Inhibition in anaerobic digestion arises when compounds present in the feedstock or generated during digestion interfere with microbial growth, enzyme activity, electron transfer, or the syntrophic interactions required for methanogenesis. Because methanogens are particularly sensitive to environmental disturbances, inhibition often becomes evident as reduced methane production, accumulation of volatile fatty acids (VFAs), and deterioration of process stability. The severity of inhibition depends not only on the total concentration of an inhibitor but also on pH, temperature, acclimation history, ionic strength, substrate composition, and the composition of the microbial community [69–71]. Ammonia inhibition is particularly important when nitrogen-rich substrates such as animal manure, sewage sludge, and some food wastes are digested. During digestion, organic nitrogen is converted to ammonium, which exists as the equilibrium pair $\text{NH}_4^+/\text{NH}_3$. The un-ionized NH_3 fraction is generally considered the more inhibitory form because it can diffuse through microbial cell membranes and disturb intracellular proton and potassium balances. Ammonia stress can alter membrane transport, energy metabolism, and the activity of methanogenic microorganisms, particularly acetate-utilizing methanogens. Consequently, accumulation of acetate and other VFAs may occur when methanogenesis becomes rate-limiting. The fraction of free ammonia increases with increasing pH and temperature, meaning that the same total ammonia concentration can have substantially different inhibitory effects under different operating conditions. Concentrations above approximately 3 g $\text{NH}_4\text{-N/L}$ have been associated with inhibition in anaerobic digestion, although reported inhibitory thresholds vary widely because of differences in substrate, temperature, acclimation, and microbial community [72,73]. Thus, a single

ammonia concentration should not be treated as a universal failure threshold.

VFA accumulation is another important indicator and cause of process imbalance. Hydrolytic and acidogenic microorganisms can continue producing acetate, propionate, butyrate, and other VFAs when the downstream acetogenic and methanogenic populations cannot consume these intermediates at a sufficient rate. Propionate accumulation is particularly useful as an indicator of deteriorating process stability because its syntrophic oxidation is thermodynamically unfavorable unless hydrogen-consuming methanogens maintain a sufficiently low hydrogen partial pressure. As VFAs accumulate, alkalinity can be consumed, and reactor pH can decline, further suppressing methanogenic activity and creating a positive feedback loop between acid accumulation and methane-production failure [52–54]. Consequently, VFA concentration and VFA/alkalinity relationships can provide earlier indications of process deterioration than methane production alone [56–58].

Sulfide inhibition is especially relevant for substrates containing substantial sulfur or sulfate. Sulfate-reducing microorganisms compete with methanogens for common substrates such as hydrogen and acetate and generate sulfide during sulfate reduction. Hydrogen sulfide can occur as dissolved H_2S and HS^- , with the proportion of the more readily membrane-permeable H_2S increasing as pH decreases. Sulfide can interfere with essential cellular enzymes and metal-containing proteins and can therefore suppress methanogenic activity. At the process level, sulfate reduction may also divert electron donors away from methanogenesis, reducing the fraction of substrate converted to methane. The inhibitory effect is therefore determined by both sulfide concentration and the balance between sulfate-reducing and methanogenic populations [74].

Heavy metals such as Zn, Cu, Ni, Co, Cr, Cd, and Pb exhibit a concentration-dependent effect. Several trace metals, including Ni, Co, and Fe, are essential micronutrients because they participate in enzymes and cofactors involved in methanogenic metabolism; however, excessive concentrations can disrupt cellular proteins, inhibit enzymes, damage cell membranes, and alter microbial

community structure [69–71,75]. The response is therefore not simply a function of total metal concentration. Metal speciation, precipitation with sulfide or carbonate, complexation with organic matter, and bioavailability can substantially modify toxicity. This explains why reported inhibitory concentrations vary among substrates and reactors. Maintaining appropriate trace-metal availability while avoiding excessive soluble-metal concentrations is therefore more effective than treating all metals as inherently toxic.

Salinity and high concentrations of soluble inorganic ions can also inhibit anaerobic digestion. Elevated concentrations of Na^+ , K^+ , Ca^{2+} , and Mg^{2+} increase osmotic stress and can interfere with cellular water balance, membrane function, and intracellular ion regulation. Methanogens may be particularly sensitive to rapid increases in salinity because adaptation requires changes in intracellular osmolytes and community structure. However, the response depends strongly on the rate of salinity increase and previous microbial acclimation. Gradual adaptation can substantially increase tolerance compared with abrupt exposure [74,76].

These inhibition mechanisms are interrelated rather than independent. For example, a nitrogen-rich substrate can increase ammonia concentrations, while high organic loading can simultaneously promote VFA accumulation. High temperature can increase the free-ammonia fraction, whereas changes in pH can modify both ammonia and sulfide speciation. Similarly, sulfide can interact with trace metals and alter their bioavailability.

Therefore, effective inhibition control requires integrated process management rather than treatment of individual inhibitors in isolation. Practical approaches include feedstock blending and co-digestion to improve C/N balance, controlled organic loading, pH and alkalinity management, gradual microbial acclimation, and selective use of adsorbents such as biochar or zeolite. Recent studies also indicate that microbial-community engineering and real-time monitoring can improve resilience to inhibitory conditions [18,20,23,77].

Importantly, inhibitor thresholds should be interpreted as operational ranges rather than

universal limits. Differences in temperature, pH, feedstock composition, reactor configuration, acclimation history, and microbial community can shift the concentration at which inhibition becomes apparent. This variability highlights the need for site-specific monitoring of ammonia, VFAs, sulfide, alkalinity, pH, and relevant trace metals when designing and operating commercial anaerobic digestion systems.

The summary of key process optimization strategies in biogas production is presented in Table 2.

5. Anaerobic Digestion Technologies

Anaerobic digestion is the cornerstone of modern biogas production, but its efficiency and applicability depend on the chosen technological configuration. Over the years, several approaches have been developed and optimized to suit different feedstocks, climates, and energy demands. This section examines the main AD technologies, highlighting their advantages, limitations, and global deployment patterns.

5.1. Batch vs. Continuous Systems

Batch digesters are simple systems where feedstock is loaded once and digested completely before the digester is emptied [87]. They are cost-effective and easy to construct, making them highly suitable for rural and small-scale applications.

However, they produce biogas discontinuously, which limits their efficiency and scalability. In contrast, continuous digesters allow for regular feeding and removal of digestate, leading to stable biogas production and higher efficiency [18]. Continuous digesters also have the advantage of being able to handle a wider range of feedstock types and qualities, making them more versatile for different applications. Additionally, the consistent production of biogas from continuous digesters makes them more reliable for energy generation. However, these systems require higher capital investment and technical expertise for operation and maintenance. Despite the higher initial costs and technical requirements, the long-term benefits and efficiency of continuous digesters make them a preferred choice for larger-scale

biogas production facilities. Figure 2 shows a schematic representation of batch and continuous anaerobic digestion systems.

Table 2. Summary of key process optimization strategies in biogas production.

Optimization Factor	Description/Strategy	Effect on Methane Yield/Process	Sources
Temperature regime	Mesophilic (30–40 °C) vs. Thermophilic (50–60 °C); Temperature-phased AD (TPAD)	Thermophilic improves hydrolysis and pathogen removal; TPAD increases yield by up to 25%	[18,22]
pH and Alkalinity	Buffering with bicarbonate, manure co-digestion, biochar amendment	Maintains pH 6.8–7.4; prevents VFA inhibition; improves microbial stability	[78,79]
Organic Loading Rate (OLR) & Hydraulic Retention Time (HRT)	OLR 2–4 kg VS/m ³ ·d; HRT 20–30 days; real-time monitoring with sensors	Prevents process overload; maximizes productivity; reduces risk of digester failure	[80–82]
Co-digestion	Combining complementary feedstocks (e.g., manure + maize silage, sludge + food waste)	Improves nutrient balance and methane yield (20–40% increase)	[83,84]
Pretreatment technologies	Mechanical, thermal, chemical, biological; e.g., steam explosion, enzymatic hydrolysis	Increases biodegradability; steam explosion boosts straw yields by over 100%	[85,86]
Inhibition control	Strategies against ammonia, sulfides, heavy metals; biochar/zeolite addition, microbial adaptation	Enhances process resilience; reduces inhibition; stabilizes methanogenesis	[23,77]

5.2. Single-Stage vs. Two-Stage Digestion

Single-stage digestion integrates hydrolysis, acidogenesis, acetogenesis, and methanogenesis in a single reactor, making it simple and cost-effective [88]. However, this simplicity can lead to lower biogas production efficiency and longer retention times for organic material.

Also, such systems often suffer from instability under high organic loads or fluctuating feedstock quality [89].

Two-stage digestion, on the other hand, separates hydrolysis/acidogenesis from methanogenesis, allowing each microbial community to operate under optimized conditions. This improves methane yields, process stability, and flexibility but requires more complex design and higher investment [90]. Figure 3 shows a comparative process schematic of single-stage and two-stage anaerobic digestion systems.

5.3. Thermophilic vs. Mesophilic Digestion

Mesophilic systems (30–40°C) are the most widely used worldwide due to their operational stability,

lower energy input, and resilience against feedstock variability [91,92]. In contrast, thermophilic systems (50–60°C) offer faster digestion rates, higher methane yields, and more effective pathogen reduction [93,94]. However, they demand more energy for heating and require precise process control to maintain stability, making them less common in resource-constrained regions [95]. Figure 4 shows a schematic representation of thermophilic versus mesophilic anaerobic digestion systems.

5.4. Co-Digestion Approaches

Co-digestion involves processing multiple feedstocks simultaneously—such as manure with food waste or crop residues—with the goal of balancing nutrients and improving methane yields. This approach can increase methane production by 20–40% compared to mono-digestion and also provides a waste management solution for diverse residues.

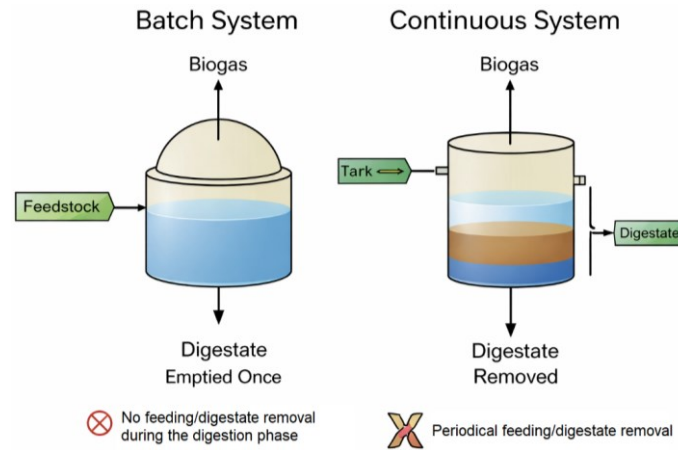


Fig. 2. Schematic representation of batch and continuous anaerobic digestion systems. Source: Authors' illustration based on [18,87].

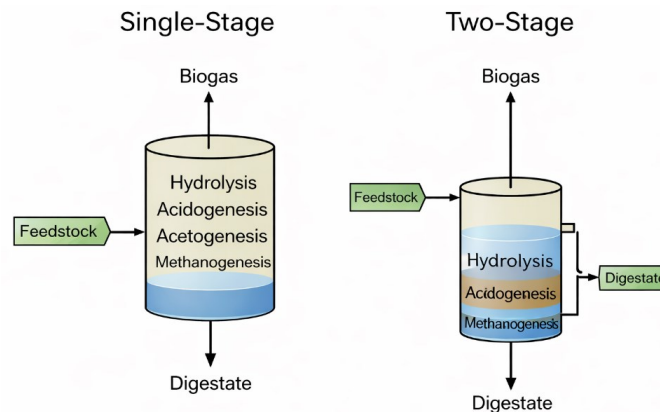


Fig. 3. Comparative process schematic of single-stage and two-stage anaerobic digestion systems. Source: Authors' illustration based on [88-90].

This practice can help utilize existing sewage treatment facilities' digestion capacity and increase OLR while reducing hydraulic retention time [96]. Co-digestion of food waste with wastewater sludge has gained momentum globally, adapting practices from the agricultural sector [96].

Nonetheless, co-digestion requires careful feedstock logistics, pre-treatment, and reactor design to avoid operational bottlenecks [97,98]. A conceptual schematic of co-digestion pathways in anaerobic digestion is shown in Figure 5.

5.5. Innovations in Digester Design

Recent advancements in digester design include plug-flow reactors, upflow anaerobic sludge blanket (UASB) reactors, membrane bioreactors, and IoT-enabled smart digesters. These designs allow for higher efficiency, compact reactor

footprints, improved effluent quality, and better process monitoring.

While promising, adopting them is still limited by higher capital costs and the need for technical expertise, especially in developing regions. Other innovations in digester design include various types, such as floating drum, fixed dome, and balloon types. The floating drum design consists of a digester chamber made of brick masonry in cement mortar with a mild steel drum for gas collection [99]. The fixed dome type is a Chinese model biogas plant with an underground brick masonry fermentation chamber and a dome for gas storage [100,101]. The balloon type, known as the plastic bag digester, uses a polyvinyl chloride bag for gas storage with additional weights for gas pressure [102].

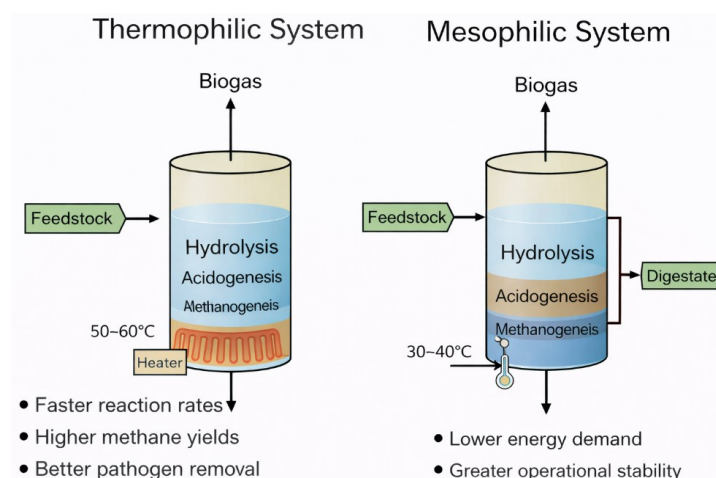


Fig. 4. Schematic representation of thermophilic versus mesophilic anaerobic digestion systems. Source: Authors' illustration based on [91–95].

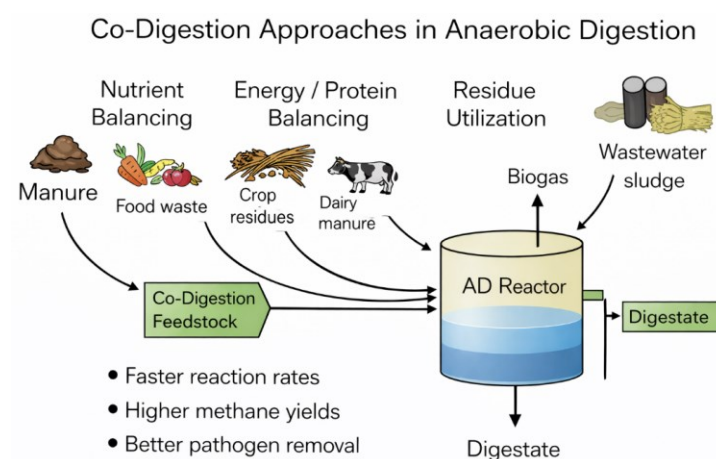


Fig. 5. Conceptual schematic of co-digestion pathways in anaerobic digestion. Source: Authors' illustration based on [96–98].

These different types of digester designs offer flexibility for varying needs and resources in different regions. The floating drum design is popular for its simplicity and ease of construction, making it suitable for low-income communities [103]. The fixed dome type is known for its durability and efficiency in gas storage, making it a reliable option for larger-scale biogas production [104,105]. The balloon-type biodigester is a cost-effective solution that can be easily transported and set up, making it ideal for temporary or mobile biogas projects [106,107].

Technologies like low-pressure balloon storage systems developed by Flexi Biogas enable mobile or temporary biogas access for schools, refugee camps, and disaster-affected communities, enhancing scalability [108].

However, deployment of such technologies must consider equity and inclusion principles to avoid reinforcing energy inequalities by privileging certain communities. While these solutions offer versatility and convenience, the business model and financing structure play a crucial role in determining market penetration and overall cost implications for users. Ultimately, the variety of digester designs available allows for biogas technology to be more accessible and adaptable to different circumstances and environments. Figure 6 shows a schematic diagram depicting innovations in anaerobic digester design.

To facilitate comparison of methane-yield performance among the major anaerobic digestion configurations discussed in this review, representative methane yields reported for cattle

manure were extracted from the literature and summarized in Table 3.

The corresponding percentage improvement was calculated relative to the reference configuration as $(Y_{\text{alternative}} - Y_{\text{reference}}) / Y_{\text{reference}} \times 100$ and plotted

(Figure 7). The comparison was restricted primarily to cattle manure to minimize variation arising from feedstock composition, while the co-digestion category represents cattle manure combined with other substrates.

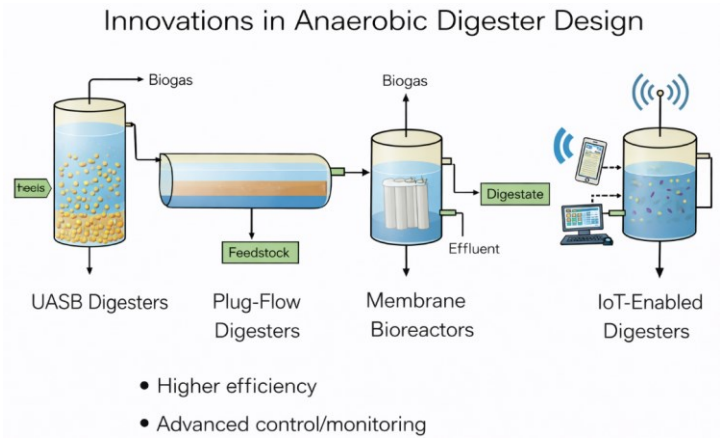


Fig. 6. Schematic representation of innovative anaerobic digester designs. Source: Authors' illustration based on [99–108].

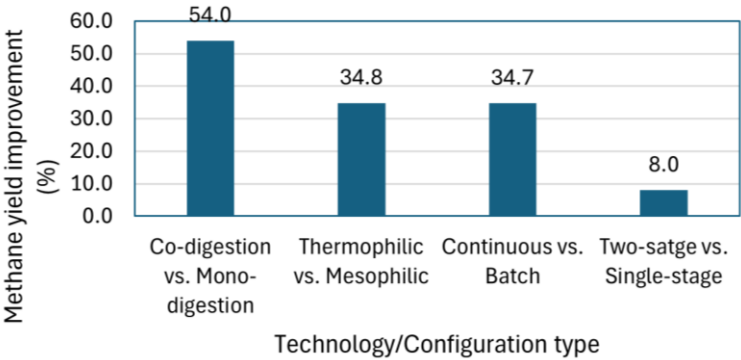


Fig. 7. Comparative methane-yield improvement associated with selected anaerobic digestion configurations using cattle manure. Source: Authors' analysis based on the studies cited in Table 3.

The resulting values are intended as comparative literature-based indicators rather than statistically pooled effect sizes, because the underlying studies differ in reactor configuration, operating temperature, hydraulic retention time, organic loading rate, and experimental scale.

6. Sustainable Energy Applications of Biogas

Biogas has emerged as a versatile renewable energy carrier with diverse applications across

household, industrial, and national energy systems. Its flexible use, ranging from direct combustion for cooking to advanced upgrading for grid injection and transportation, makes it a critical technology in the global transition to sustainable energy. The following subsections outline key application pathways.

Table 3. Comparative overview of anaerobic digestion technologies with global deployment examples.

Technology/ Configuration Type	Description	Advantages	Limitations	Global Deployment Examples	Representative methane yield (m ³ CH ₄ /kg VS)	Sources
Batch systems	Feedstock loaded once, digested fully, then emptied	Low cost, simple design, suitable for rural/small-scale use	Discontinuous gas output, lower efficiency	Common in rural India and Nepal (fixed-dome digesters)	0.176	[18,109,110]
Continuous systems	Feedstock added and digestate removed periodically	Stable gas output, higher efficiency, scalable	Higher cost, requires maintenance and monitoring	Widely used in EU farms and US wastewater plants	0.237	[110-112]
Single-stage digestion	All microbial processes in one reactor	Simple design, low capital cost	Risk of instability, less efficient under high loads	Deployed in small-scale plants across Africa and SE Asia	0.176	[112-114]
Two-stage digestion	Hydrolysis/acidogenesis separated from methanogenesis	Optimized conditions, higher yields, stable	More complex, higher capital and operating costs	Used in Germany and Denmark for high-efficiency plants	0.190	[114,115]
Mesophilic digestion	Operates at 30–40°C	Stable, energy-efficient, widely used	Lower reaction rates, slower pathogen reduction	Dominant in China's household-scale digesters	0.155	[111,116]
Thermophilic digestion	Operates at 50–60°C	Faster digestion, higher yields, better pathogen removal	Higher energy demand, less stable, needs close control	Adopted in Scandinavian countries for waste-to-energy	0.209	[116,117]
Mono-digestion	Processing of a single, unblended organic feedstock substrate	Simplified supply chain logistics	High risk of nutrient imbalance	Mono-stream agricultural digesters across Germany and China	0.163	[18,110]
Co-digestion	Combines two or more feedstocks	Balances nutrients, increases methane yields (20–40%)	Requires logistics and pre-mixing	Spain and Italy: manure + food waste; USA: dairy + crop residues	0.251	[110,118]
Innovative designs	Plug-flow, UASB, membrane bioreactors, IoT-enabled digesters	Higher efficiency, compact, digital optimization	Higher initial investment, requires technical expertise	Netherlands: UASB for wastewater; US: plug-flow for cattle manure; Japan: smart IoT digesters	NA	[119,120]

6.1. Household Cooking and Heating

In many developing countries, biogas digesters provide an affordable and cleaner alternative to traditional biomass fuels, such as firewood and charcoal.

Household-scale digesters (1–10 m³ capacity) are widely deployed in rural Asia and Africa, offering reliable fuel for daily cooking needs [121,122]. In addition to cooking, biogas can also be used for heating purposes in homes, providing a more efficient and eco-friendly option compared to traditional fuels [123]. The use of biogas for domestic cooking and heating purposes not only reduces deforestation but also improves indoor air quality, mitigating health risks associated with smoke inhalation [124]. Case studies from India, China, Kenya, and some other countries show that household biogas systems can offset a good percentage of traditional biomass use [125].

6.2. Electricity and Heat Generation

At larger scales, biogas is commonly used in combined heat and power (CHP) units, which can achieve energy conversion efficiencies of 60–80% [126,127]. These systems generate both electricity and heat, making them even more efficient. In addition to reducing greenhouse gas emissions, biogas CHP units provide a reliable source of energy that can help communities become more self-sufficient.

The success of biogas in various countries demonstrates its potential to transform the energy sector and contribute to a more sustainable future. In Europe, the flexibilization of biogas plants can contribute significantly to local power grids by enabling the achievement of around 10 to 15 GW of flexible peak power, alleviating the power grid during high residual load periods [128]. In industrial settings, CHP integration improves energy self-sufficiency, particularly in agro-industries such as sugar mills, breweries, and palm oil refineries, where waste feedstocks are readily available [129].

6.3. Upgraded Biogas (Biomethane) for Grid Injection

Raw biogas typically contains 50–65% methane, along with CO₂, H₂S, and trace contaminants [130,131]. Upgrading technologies such as pressure

swing adsorption, water scrubbing, and membrane separation can produce biomethane (>95% CH₄), suitable for injection into natural gas grids [24,27,132]. The production of biomethane through upgrading technologies allows for the injection of high-quality methane into natural gas grids, increasing the overall efficiency and sustainability of the energy system. This process not only reduces greenhouse gas emissions but also provides a valuable source of renewable energy that can be utilized during high residual load periods. Some countries in Europe have successfully integrated biomethane into national grids, displacing fossil natural gas and reducing carbon emissions [133,134].

6.4. Biogas in Transportation

Biomethane can also be compressed (CBG) or liquefied (LBG) to serve as transport fuel [135]. This allows for the decarbonization of the transportation sector, as vehicles fueled by biomethane produce significantly lower emissions compared to traditional fossil fuels. The use of biomethane in transportation can help reduce air pollution and combat climate change, making it a sustainable alternative for reducing greenhouse gas emissions across multiple sectors. In Sweden, biomethane accounts for more than 60% of the gas used in transport, powering buses, trucks, and private vehicles [136]. Switching from diesel to biomethane can significantly reduce greenhouse gas emissions on a life-cycle basis, with potential GHG emission reductions of 27–62% compared to conventional natural gas passenger vehicles or 41–70% compared to petrol vehicles [25,137]. Emerging initiatives in China and India are also promoting large-scale adoption of biomethane as a transport fuel [138]. In India, biomethane generation potential from wastes could meet a significant portion of the country's road transport fuel demand [139]. Biomethane production is seen as a viable option to displace fossil fuels and reduce greenhouse gas emissions in both countries [140].

6.5 Biofertilizer Production from Digestate

An often overlooked but equally important application of biogas systems is the use of digestate as a nutrient-rich biofertilizer. Digestate contains nitrogen, phosphorus, and potassium in plant-available forms, reducing the need for synthetic fertilizers [141,142]. In Europe, over 30%

of digestate from biogas plants is directly applied in agriculture, supporting circular bioeconomy practices [143]. This practice not only helps to reduce the environmental impact of agriculture by decreasing reliance on chemical fertilizers, but it also closes the nutrient loop by returning organic matter back to the soil [144]. Additionally, using digestate as a biofertilizer can improve soil health and fertility, leading to increased crop yields and overall agricultural sustainability. By integrating biofertilizer production into biogas systems, we can maximize the benefits of organic waste management while promoting more sustainable farming practices [145]. For example, a dairy farm could use the digestate from its biogas system as a biofertilizer to replenish nutrients in the soil after harvesting crops [146,147]. This would not only reduce the farm's reliance on synthetic fertilizers but also improve soil health and promote more sustainable agricultural practices [148]. Additionally, the use of biofertilizers can lead to increased crop yields and overall farm productivity [149].

These examples also illustrate a broader geographical pattern: developed economies increasingly emphasize integrated medium- and large-scale systems for CHP, biomethane upgrading and grid or transport applications, whereas developing economies have relied more

heavily on decentralized household and community systems aimed at cooking, heating and local energy access. However, this distinction is not absolute, and technology selection remains strongly dependent on feedstock density, infrastructure, financing and local energy markets. Country-specific examples of biogas applications are presented in Table 4.

7. Challenges and Future Perspectives

Despite its proven benefits, large-scale deployment of biogas technologies faces several technical, economic, social, and policy-related challenges that constrain their full potential.

Addressing these issues is critical to ensuring biogas plays a central role in the global transition to renewable energy systems.

7.1. Technical and Operational Challenges

(i) **Feedstock variability:** Biogas yield strongly depends on the type, composition, and seasonal availability of feedstock. Agricultural residues and municipal solid waste often suffer from inconsistent supply chains and contamination, leading to fluctuating methane yields [18].

Process inefficiencies: Anaerobic digestion is sensitive to operational conditions (pH, temperature, carbon-to-nitrogen ratio).

Table 4. Country-specific examples of biogas applications.

Country / Region	Scale / Deployment	Key Figures	Outcomes / Notes	Sources
India	Household-scale digesters under NBMMP; community projects	~4.96 million plants installed; potential for 12 million units; ~29.16 billion m ³ /year manure-based potential	Replaces firewood/kerosene; community biogas plants supply 20–22 households (Bihar); 8,000 rural units (Karnataka)	[150,151]
Asia (overall)	Household digesters dominate	~45.03 million digesters, 99.72% household	Largest global deployment; key countries: China, India, Nepal, Vietnam	[152]
European Union (EU-27)	Medium-large plants, CHP, biomethane grid injection	729 biomethane plants (Germany: 232; France: 131; UK: 80); 3 bcm biomethane + 15 bcm biogas in 2022; target: 35 bcm biomethane by 2030	Strong policy support under REPowerEU; contributes >10 GW CHP	[120,153]
Sweden	Transport biomethane, farm-scale AD	Biogas from AD: 2 TWh (2020), target 7 TWh/year by 2030; ~60% of transport gas fuel is biomethane	Strong circular economy focus; integration with waste and agriculture	[154,155]

(ii) Instabilities such as **acidification and ammonia inhibition** reduce process robustness [156].

(iii) **Upgrading technologies:** Although upgrading technologies (membrane separation, pressure swing adsorption, water scrubbing) in anaerobic digestion are advancing, they remain **capital-intensive** and often unaffordable in low-income settings [157].

7.2. Methane Leakage and Life-Cycle Climate Performance

Although anaerobic digestion can reduce greenhouse-gas emissions by recovering methane from organic wastes and displacing fossil fuels, its climate benefit depends strongly on controlling unintended methane releases throughout the biogas value chain. Methane can escape from digesters, pressure-relief devices, gas-storage systems, upgrading units, pipelines, engines, flares, and digestate storage or handling. Because methane has a much higher short-term climate impact than carbon dioxide, relatively small losses of produced methane can substantially reduce the net climate benefit attributed to biogas systems [20,158,159].

Methane losses from digesters and gas-handling infrastructure arise primarily from defective membranes, inspection hatches, pipe connections, pressure-relief valves, mixer shafts, valves, compressors, and other gas-bearing components. Their magnitude can vary considerably among plants because of differences in equipment design, maintenance, operating pressure, and monitoring practices. A harmonized field study of 33 biogas plants in Austria, Germany, Sweden, and Switzerland found individual leakages ranging from 0 to 2.1% of methane production, with a median of 0.1% [158].

A larger Danish survey of 69 plants, however, found total plant methane losses ranging from 0.3 to 40.6% of methane production, demonstrating the importance of site-specific measurement and maintenance [159]. Pressure-relief valves were identified as a particularly common source of emissions, occurring at 53% of the investigated Danish plants [159].

Digestate storage can represent an important post-digestion source of methane. Residual

biodegradable organic matter in digestate can continue to produce methane after leaving the digester, particularly when storage is poorly sealed, residence times are short, or digestate is stored without gas recovery. In harmonized European measurements, non-gastight digestate storage showed methane emissions as high as 5.6% of the methane produced [158]. Field measurements at two agricultural biogas plants reported digestate-storage losses of 5.8% and 10.7% of biogas methane, respectively, making digestate storage the largest identified source at both facilities [160]. These findings indicate that maximizing methane recovery inside the digester does not necessarily ensure low system-wide methane emissions; post-digestion management must also be incorporated into environmental assessments.

Biogas upgrading can introduce additional methane slip. Methane losses depend strongly on the upgrading technology and its operating conditions. In the harmonized field measurements, median methane losses from upgrading units were below 0.1% for chemical scrubbers, approximately 0.1% after exhaust-gas treatment, and 2.9% for the water-scrubbing units investigated [158]. Earlier measurements of commercially operating upgrading plants similarly identified methane emissions from upgrading equipment as an important component of overall plant losses [161]. Consequently, selection of an upgrading technology should consider not only methane purity, energy consumption, and cost but also methane recovery efficiency and residual methane emissions.

Methane slip from energy-conversion equipment is another pathway that can reduce the climate performance of biogas utilization. In the 33-plant field study, median methane loss associated with gas engines was 1.6% of the input methane, while pilot injection units showed a median loss of approximately 3.0% [158]. Although these losses may be smaller than emissions from poorly managed digestate storage or major plant leaks, they become relevant when evaluating biomethane or biogas systems on a life-cycle basis. Engine operating conditions, combustion technology, maintenance, and exhaust-gas treatment influence the magnitude of methane slip. The life-cycle implication of methane leakage is nonlinear

in practical terms because the climate benefit of biogas depends on the balance between avoided emissions and additional emissions caused by the biogas system. When methane losses are underestimated, life-cycle assessments can substantially overestimate the climate benefit of anaerobic digestion, particularly for systems in which methane is recovered for electricity generation or upgraded to biomethane. This is especially important when biogas replaces relatively low-carbon electricity or natural gas, because the avoided fossil emissions are smaller and the relative importance of fugitive methane becomes greater. Recent field evidence therefore supports the use of measured or technology-specific methane emission factors rather than assuming a single universal leakage rate [158-160]. Methane leakage control should consequently be treated as a core process-performance indicator rather than only an environmental compliance issue. Effective measures include routine leak detection and repair, pressure-relief management, gas-tight digestate storage with methane recovery, appropriate upgrading technology selection, optimization of engine combustion, and continuous or periodic methane monitoring. Integrating these measures into life-cycle assessment and techno-economic analysis can provide a more realistic estimate of the net environmental and economic performance of biogas systems. This is particularly important for developing regions, where limited maintenance infrastructure and monitoring capacity may increase the risk that small, persistent leaks remain undetected. Thus, future biogas deployment should prioritize not only methane production and recovery efficiency but also whole-system methane-loss minimization.

7.3. Economic and Financial Constraints

The economic viability of anaerobic digestion is strongly dependent on plant scale, feedstock availability, technology selection, energy utilization pathway, financing conditions, and the value assigned to co-products and avoided environmental impacts. Consequently, a technology that is technically superior in methane production may not necessarily be the most economically attractive option. Capital

expenditure for digesters, gas-cleaning and upgrading equipment, storage infrastructure, electricity-generation units, and grid or gas-network connections can constitute a major barrier, particularly where financing costs are high, and energy markets are weakly developed. Recent techno-economic studies demonstrate that project viability is therefore highly context-specific rather than determined solely by methane yield [162-165]. Economic assessment should consider capital expenditure (CAPEX), operating expenditure (OPEX), levelized cost of energy or biomethane (LCOE/LCOB), net present value (NPV), internal rate of return (IRR), benefit-to-cost ratio, and payback period rather than relying on a single indicator. For example, a positive NPV indicates that discounted project revenues exceed investment and operating costs over the selected project lifetime, whereas IRR provides a measure of the return relative to the investment. Payback period is easier to communicate to investors but does not account adequately for the time value of money and cash flows occurring after capital recovery. LCOE or an equivalent cost-per-unit-energy metric is useful for comparing alternative energy pathways, but its value is highly sensitive to plant capacity factor, methane yield, energy conversion efficiency, feedstock transport distance, financing rate, plant lifetime, and replacement costs. Therefore, reported economic indicators from different studies should not be compared without considering their system boundaries, currency year, discount rate, plant scale, and assumptions.

Recent case studies illustrate this context dependence. Economic assessment of anaerobic digestion of olive-oil industry effluents in Greece demonstrated that the attractiveness of AD depends strongly on the treatment configuration and the economic value assigned to the recovered energy [162]. Similarly, a recent assessment of a dairy-farm biogas plant in Poland showed that investment efficiency depends on the scale and operating characteristics of the plant, as well as the utilization of the generated biogas [163]. For decentralized systems in sub-Saharan Africa, techno-economic modelling indicates that locally available feedstock and avoided conventional energy expenditure can improve project viability,

whereas high initial investment, maintenance requirements and weak infrastructure can remain important constraints [165].

Revenue diversification is therefore central to improving project economics. Electricity or biomethane sales represent only one component of potential revenue. Additional value can be obtained from avoided waste-treatment costs, heat recovery, digestate utilization, tipping fees, nutrient recovery, carbon credits and renewable-energy certificates. Digestate valorization is particularly important because the recovery of nitrogen, phosphorus and organic matter can reduce dependence on synthetic fertilizers and create an additional product stream [26,166]. However, these benefits should only be incorporated into economic calculations when realistic local markets, avoided costs or policy incentives exist. Assuming full revenue from digestate or carbon credits without considering market access can substantially overestimate project profitability.

The comparison between developed and developing economies is especially important. In countries with mature biomethane markets, established gas infrastructure and stable renewable-energy policies, upgrading biogas to biomethane can create additional revenue through grid injection or transport-fuel markets. In contrast, decentralized systems in developing countries may be economically preferable when biogas is used directly for cooking, heating, or electricity generation because expensive upgrading and gas-grid infrastructure can be avoided [121,122,165]. Thus, economic optimization should be based on the most appropriate end-use pathway rather than assuming that biomethane upgrading is universally superior to direct biogas utilization.

Financing conditions can further change the ranking of competing technologies. High interest rates increase the present value of future operating costs and reduce the attractiveness of capital-intensive upgrading, advanced pretreatment and large centralized plants. Conversely, concessional financing, carbon revenues, feed-in tariffs and renewable-gas incentives can substantially improve project economics. This explains why the same AD technology can be commercially attractive in one country but financially marginal

in another. Economic assessments should therefore report sensitivity to feedstock price, energy price, discount rate, methane yield, plant utilization, CAPEX, OPEX and policy incentives rather than presenting a single deterministic profitability value.

7.4. Life-Cycle Environmental Performance and Trade-Offs

The environmental performance of biogas systems cannot be evaluated solely from the amount of renewable energy produced. A life-cycle assessment (LCA) must consider feedstock collection and transport, pretreatment, anaerobic digestion, biogas cleaning and upgrading, energy conversion, digestate storage and utilization, infrastructure, and avoided conventional waste-management and fossil-energy pathways. Depending on the system boundary and allocation procedure, the same AD technology can therefore produce substantially different greenhouse-gas (GHG) outcomes.

The climate benefit of biogas is primarily associated with three mechanisms: (i) avoiding uncontrolled methane emissions that would otherwise occur during decomposition of organic wastes, (ii) displacing fossil fuels or grid electricity, and (iii) recovering nutrients through digestate application and thereby potentially avoiding part of the environmental burden associated with synthetic fertilizer production. These benefits must be balanced against emissions from feedstock collection and transportation, auxiliary electricity and heat consumption, methane leakage, digestate storage, combustion-related emissions, and energy-intensive upgrading processes [25,124,137,139].

Quantitative assessments demonstrate that the end-use pathway can substantially influence the climate performance of biomethane. For transport applications, life-cycle assessments have reported GHG reductions of approximately 27–62% relative to conventional natural-gas vehicles and 41–70% relative to petrol vehicles, although the magnitude depends on the feedstock and supply-chain configuration [25,137]. These ranges demonstrate that biomethane can provide substantial climate benefits, but they should not be interpreted as universal values because feedstock origin, methane

leakage, upgrading efficiency, vehicle technology and allocation assumptions differ among studies. Feedstock choice is particularly important. Waste-derived biogas can achieve greater climate benefits when the baseline scenario includes methane emissions from uncontrolled decomposition or conventional waste treatment. In contrast, digestion of purpose-grown energy crops can involve additional burdens from cultivation, fertilizer use, land occupation, harvesting and transport. Consequently, the environmental advantage of AD is generally stronger when it simultaneously provides waste-treatment, methane-recovery, and fossil-energy-substitution benefits rather than relying solely on energy production.

Digestate management also produces important environmental trade-offs. Appropriate application of digestate can recycle nitrogen, phosphorus and organic matter and reduce the requirement for synthetic fertilizers [141–149]. However, storage and land application can generate ammonia, nitrous oxide, and residual methane emissions if poorly managed. Thus, digestate should not automatically be counted as an environmental credit. The magnitude of the credit depends on nutrient availability, crop requirements, fertilizer substitution efficiency, storage conditions, soil characteristics and application practices.

Methane leakage is particularly important because it can substantially reduce the climate advantage of AD. Methane losses may occur during digestion, gas storage, upgrading, combustion, and digestate management. Consequently, LCA models that use optimistic default leakage factors may overestimate GHG mitigation.

The principal environmental trade-off is therefore between energy recovery and the emissions associated with producing, processing, and utilizing the biogas system itself. Pretreatment can increase methane production but may increase electricity or heat demand; upgrading can produce high-quality biomethane but introduces additional energy requirements and methane-slip risks; centralized plants can benefit from economies of scale but require longer feedstock-transport distances; and digestate application can reduce fertilizer demand but may generate field emissions. These interactions explain why no single AD

configuration can be considered environmentally optimal under all conditions.

For future assessments, LCA studies should therefore report consistent functional units, system boundaries, allocation procedures, methane-leakage assumptions, and counterfactual scenarios.

Combining LCA with techno-economic analysis is particularly valuable because a process may have a favourable carbon balance but remain economically unattractive, or may be economically profitable while providing only modest environmental benefits. Integrated techno-economic and life-cycle assessment should consequently be used to identify configurations that simultaneously deliver acceptable cost, energy recovery, and GHG performance.

7.5. Policy and Institutional Barriers

(i) **Policy inconsistency:** Many countries lack stable long-term biogas policies. Frequent policy changes in feed-in tariffs or renewable energy incentives discourage investment [163]. This lack of stability creates uncertainty for potential investors in the biogas sector. Additionally, the absence of clear regulations and standards for biogas production and utilization further hinders its growth. Without a supportive policy framework in place, the potential of biogas to contribute significantly to the renewable energy mix remains unrealized. Addressing these policy and institutional barriers is crucial for unlocking the full potential of biogas as a sustainable energy source.

(ii) **Weak rural support:** In regions like Sub-Saharan Africa and South Asia, programs promoting household digesters often face challenges with maintenance, user training, and spare-part availability, leading to low long-term adoption rates [167]. These challenges highlight the need for stronger rural support systems to ensure the successful implementation and continued use of biogas technologies. Initiatives focusing on training local technicians, establishing supply chains for spare parts, and offering ongoing support to users are essential for overcoming these barriers. By strengthening rural support networks, countries can increase the uptake of biogas technology and harness its potential as a sustainable energy solution for rural communities.

(iii) **Grid access limitations:** In countries with weak infrastructure, upgraded biomethane injection into natural gas grids is limited or non-existent [168]. This can hinder the widespread adoption of biogas technology, as rural communities may not have access to the necessary infrastructure to utilize the energy produced. In order to address this issue, government investment in upgrading grid infrastructure and expanding biomethane injection capabilities is crucial. By improving grid access, countries can maximize the benefits of biogas technology and create a more sustainable energy system for all.

7.6. 7.6 Social Acceptance and Knowledge Gaps

(i) **Awareness and training:** Lack of awareness and training is a primary factor in the high failure rate of household-level biogas projects in developing countries, leading to poor operational practices and premature abandonment. Studies show that many users, often lacking formal education or technical training, are unable to manage the complex yet delicate biological processes of a digester, resulting in low gas production and negative perceptions of the technology [167].

(ii) **Cultural barriers:** Cultural perceptions and social stigmas surrounding the handling of waste are significant, often under-reported barriers to the adoption of waste-to-energy (WtE) technologies, particularly in rural or traditional communities. In some cultures, particularly in parts of India, handling human excreta (night soil) is associated with rigid caste hierarchies and notions of "purity and pollution," making the use of toilet-linked biogas systems a taboo [169].

(iii) **Equity issues:** Equity issues in the adoption of biogas systems often stem from a misalignment between the beneficiaries (primarily women and marginalized groups) and the decision-makers (often male household heads). While women benefit most from reduced drudgery (time saved from firewood collection) and improved health (reduced indoor air pollution), they are typically excluded from decisions regarding the investment, installation, and location of biogas technology [170].

7.7. Developed versus Developing Countries: Technology, Economics and Implementation

The development and deployment of anaerobic digestion technologies differ substantially between developed and developing countries because technological maturity is influenced not only by feedstock availability but also by infrastructure, financing, policy support, technical capacity, energy markets, and the intended end use of biogas. The contrast is therefore not simply one of technology availability; rather, it reflects differences in the scale, sophistication, integration, and institutional support of biogas systems. In developed economies, particularly in Europe, anaerobic digestion has increasingly progressed from conventional farm- and wastewater-based digestion toward integrated biogas and biomethane systems. Medium- and large-scale plants commonly incorporate combined heat and power (CHP), advanced gas cleaning, biomethane upgrading, grid injection, and, increasingly, flexible operation in response to electricity demand [120,133,134]. The European Union had approximately 729 biomethane plants in operation, with Germany, France and the United Kingdom accounting for a substantial proportion of installed capacity, while policy initiatives such as REPowerEU have established ambitious targets for increasing biomethane production [153]. Sweden provides a further example of mature market integration, where biomethane has become an important transport fuel and biogas production is increasingly integrated with municipal waste management and agriculture [154,155]. These developments demonstrate a transition from biogas as a waste-treatment technology toward integrated renewable-gas and circular-bioeconomy systems.

In contrast, developing countries have generally experienced greater deployment of decentralized and household-scale digesters, particularly in rural areas of Asia and Africa. India, China, Nepal and Vietnam account for a large share of household digester deployment, with household systems primarily providing cooking fuel and, in some cases, small-scale heating and electricity [121,122,152]. India's national biogas programs have supported millions of household and community-scale digesters, while community systems have been

used to supply multiple households with locally produced biogas [150,151]. These systems are technically less complex than large biomethane plants, but their suitability to rural conditions is an important strength because they can use locally available manure and organic residues without requiring gas-grid infrastructure.

The difference in technological maturity is therefore reflected primarily in the degree of system integration. Developed-country systems are more likely to incorporate automated monitoring, advanced upgrading, CHP, gas-grid injection, digestate processing and centralized waste logistics, whereas developing-country systems more commonly emphasize low-cost digesters, direct combustion for cooking, decentralized electricity generation and local fertilizer recovery. This does not necessarily imply that decentralized systems are technologically inferior. For communities without reliable electricity grids, gas networks, or high-quality maintenance services, a relatively simple fixed-dome, plug-flow, or balloon digester may provide a more appropriate technology than an advanced biomethane upgrading plant. The appropriate technology is therefore determined by the local energy system and resource conditions, rather than by technological sophistication alone [103-109].

Economic conditions further reinforce this divergence. Large, centralized digesters and biomethane-upgrading plants require substantial capital investment in civil infrastructure, gas purification, compression, storage, electricity generation, or grid connection. These investments are more readily supported in developed markets where renewable-energy incentives, carbon policies, established natural-gas infrastructure and mature financing mechanisms can improve revenue certainty [133,134]. In developing economies, high interest rates, limited access to long-term financing, weak gas infrastructure and relatively low ability of rural households to pay for equipment can make capital-intensive systems difficult to implement [5,6,121,122]. Under these circumstances, decentralized digesters that primarily substitute purchased LPG, kerosene, firewood, or electricity can have greater practical economic value even when their absolute energy output is modest. The economic comparison is

therefore strongly dependent on the value of the displaced energy and the availability of additional revenue streams. In developed countries, revenue can be obtained from electricity, heat, biomethane, grid injection, transport fuel, waste-treatment fees, renewable-energy incentives and carbon markets. In developing regions, the principal benefits may instead be avoided expenditure on cooking fuels, reduced dependence on traditional biomass, improved waste management, and the recovery of digestate for agricultural use [108,121,122]. Consequently, applying the economic criteria of a European biomethane plant directly to a rural African household digester could give a misleading assessment of its value because the two systems provide fundamentally different services.

Implementation barriers also differ systematically between the two contexts. Developed countries generally possess stronger technical-service networks, standardized equipment, established environmental regulations, reliable electricity and gas infrastructure, and better access to finance. Their principal barriers are therefore increasingly associated with feedstock competition, permitting, grid capacity, market uncertainty, methane leakage, operating costs, and the need to maintain profitability under changing energy prices and policy incentives [133,134,168]. Developing countries face a broader set of structural barriers, including inadequate financing, unreliable electricity and transport infrastructure, limited access to spare parts, insufficient technical training, weak maintenance networks, inconsistent policy support, and difficulties in establishing reliable feedstock-collection systems [6,104,107,121,122,167]. Feedstock logistics represent another important distinction. Developing regions possess substantial quantities of agricultural residues, animal manure and municipal organic waste, but these resources are frequently dispersed, seasonal, and poorly integrated into formal collection systems. The resulting variability can limit the feasibility of centralized plants despite high theoretical biogas potential [2,5,6]. Developed countries generally have more organized waste-management and agricultural supply chains, allowing large plants to secure relatively consistent feedstock supplies.

However, this advantage can be offset by greater transportation distances, stricter environmental regulations, and competition among alternative waste-treatment pathways.

The comparison also reveals an important technology-selection trade-off. Advanced upgrading and biomethane-grid systems can maximize the market value of methane where suitable infrastructure exists, but they introduce additional capital, energy and maintenance

requirements. In many developing regions, direct utilization of biogas for cooking, heating or decentralized electricity generation may provide greater overall sustainability because it avoids expensive upgrading and gas-distribution infrastructure. Conversely, where urban organic waste streams are sufficiently concentrated and reliable, medium-scale or centralized digesters combined with CHP or biomethane production may become economically attractive.

Table 5. Comparative characteristics of biogas deployment in developed and developing economies.

Dimension	Developed economies	Developing economies
Typical deployment scale	Medium- to large-scale agricultural, municipal and wastewater plants	Predominantly household, farm and community-scale systems, with emerging medium/large plants
Technology maturity	Advanced AD, CHP, biomethane upgrading, grid injection, automation and digital monitoring	Established low-cost digesters; increasing adoption of improved and modular systems
Typical energy pathway	CHP, grid electricity, biomethane injection and transport fuel	Cooking, heating, decentralized electricity and local energy supply
Feedstock supply	More organized collection and relatively reliable supply chains	High resource availability but dispersed, seasonal and less formalized supply chains
Infrastructure	Established electricity/gas networks and waste-management systems	Often limited electricity, gas-grid, transport and waste-collection infrastructure
Financing	Greater access to commercial finance, subsidies, carbon markets and renewable-energy incentives	Limited access to long-term finance; dependence on grants, microfinance and development programmes
Main economic challenge	Market competition, policy uncertainty, operating costs and investment returns	High upfront cost, financing constraints and limited ability to pay
Main technical challenge	Feedstock competition, process optimization, methane leakage and upgrading efficiency	Maintenance, spare parts, technical skills and process stability
Policy environment	More developed renewable-gas standards, incentives and environmental regulations	Policy frameworks often fragmented or inconsistent
Primary implementation barrier	Market and regulatory integration	Finance, infrastructure, maintenance and technical capacity
Most appropriate development priority	Advanced biomethane, flexible CHP, nutrient recovery and system integration	Reliable decentralized systems, local manufacturing, training and gradual scale-up

Note: The comparison represents broad deployment patterns identified in the literature and should not be interpreted as a strict division between countries. Developing countries also operate large-scale AD and biomethane plants, while decentralized systems remain present in developed economies.

Thus, decentralization should not be regarded as an inherent requirement for developing countries, nor should large-scale upgrading be assumed to be the preferred pathway in developed countries; technology selection should follow feedstock density, energy demand, infrastructure availability, and market conditions. Overall, the evidence indicates that the future development pathway of biogas will likely remain regionally

differentiated. Developed countries are positioned to advance toward highly integrated biomethane, CHP, digital monitoring, nutrient-recovery, and circular-bioeconomy systems, whereas developing countries have substantial opportunities to expand decentralized and community-scale systems while progressively developing medium- and large-scale infrastructure where feedstock and markets justify investment. International technology transfer

should therefore emphasize adaptation rather than simple replication. Low-cost designs, local manufacturing, technician training, modular upgrading, microfinance and community-based ownership models may be more effective for accelerating deployment in resource-constrained regions than transferring capital-intensive systems designed for mature European markets [104,107,121,122,165]. The comparative characteristics of biogas deployment in developed and developing economies is presented in Table 5.

7.8. Future Perspectives

(i) **Integration with hydrogen and power-to-gas (P2G):** Integrating green hydrogen (H₂) and Power-to-Gas (P2G) technologies with anaerobic digestion (biogas production) is a highly efficient approach to producing renewable synthetic methane (e-methane). By combining excess renewable electricity (via electrolysis) with the CO₂ naturally present in raw biogas (typically 30–50% of the composition), the methane content can be increased to over 90–99%, resulting in high-quality Renewable Natural Gas (RNG) [164].

(ii) **Advanced bioenergy conversion technologies:** Beyond conventional biogas utilization, advances in bioelectrochemical and materials-based energy-conversion technologies illustrate broader opportunities for coupling biological processes with advanced functional materials. Ahamed et al. [171], for example, developed a silver-nanoparticle-anchored zinc oxide scaffold for an enzymatic biofuel cell, demonstrating the potential of engineered nanomaterials in renewable bioenergy conversion. Although enzymatic biofuel cells are distinct from anaerobic digestion and are not a direct route for large-scale biogas production, such developments illustrate the broader evolution of bioenergy technologies toward integrated biological, catalytic, and materials-based systems. For biogas applications, the practical relevance of such emerging technologies will depend on their scalability, energy efficiency, economic feasibility, material sustainability, and potential for integration with established renewable-energy systems.

(iii) **Digitalization and smart monitoring:** Digitalization, specifically through the integration

of Internet of Things (IoT)-based sensors, Artificial Intelligence (AI)-driven process control, and real-time monitoring, is transforming anaerobic digestion (AD) by shifting it from manual, reactive management to automated, proactive optimization. This technological integration can increase biogas production by up to 53–78% and significantly reduce operational downtime [172].

(iv) **Circular bioeconomy models:** The valorization of digestate—the nutrient-rich byproduct of anaerobic digestion—as a biofertilizer represents a core strategy in the circular bioeconomy, enabling biogas plants to transition into bio-refineries that maximize resource efficiency. By integrating digestate with agriculture, these systems turn waste management into a source of sustainable, organic fertilizers, reducing reliance on fossil-fuel-intensive synthetic alternatives [166].

(v) **Policy frameworks:** Policy frameworks, including stronger carbon pricing, renewable gas mandates, and blending obligations, are critical in improving the competitiveness of biogas and biomethane against traditional fossil fuels. These measures, particularly when combined with targeted financial incentives, help address the higher production costs of renewable gas and foster market growth [173].

(vi) **Scalability in developing regions:** Decentralized micro-digester networks combined with microfinance can significantly accelerate household adoption of biogas in Africa and South Asia by improving access to clean energy and reducing waste management burdens [165]. These systems provide autonomous energy and organic fertilizers, with community-scale plants addressing urban waste challenges.

7.9. Emerging Technologies: Readiness, Limitations and Commercialization Prospects

The rapid development of anaerobic digestion has produced a range of emerging technologies aimed at improving process stability, methane recovery, energy efficiency, resource recovery, and system integration. However, these technologies differ substantially in their technological maturity. Demonstration of improved methane production under laboratory conditions does not necessarily indicate readiness for commercial deployment.

Their practical viability must also be assessed in terms of scale-up performance, long-term operational stability, energy requirements, capital and operating costs, environmental implications, infrastructure compatibility, and maintenance requirements. Accordingly, the following discussion critically evaluates the principal emerging technologies covered in this review according to their current readiness, major limitations and prospects for commercialization.

Advanced process configurations, including two-stage digestion, temperature-phased digestion, membrane-assisted systems and optimized continuous reactors, are relatively mature because they build on established anaerobic digestion principles and infrastructure. Their principal limitations are additional capital investment, more complex process control and, in some cases, increased pumping or heating requirements. Their commercialization prospects are therefore comparatively strong where improved process stability, higher loading rates or increased methane productivity can compensate for the additional investment [18,82,87,90].

Advanced biogas upgrading, particularly membrane separation, pressure swing adsorption, and water or chemical scrubbing, has a relatively high technological readiness because these technologies are already used commercially for biomethane production. Their principal challenges include energy consumption, contaminant removal, membrane fouling or degradation, methane slip, and the economics of small-scale deployment [24,130-132,174]. Future improvements are likely to focus on reducing methane losses and energy consumption while developing modular upgrading systems suitable for smaller plants.

Digitalization, Internet-of-Things monitoring, and artificial intelligence have strong near-term commercialization potential because they can be incorporated into existing digesters without fundamentally changing the biological conversion process. Sensors and predictive models can support real-time monitoring of pH, temperature, organic loading, gas composition, and process instability. However, the reliability of such systems depends on sensor quality, data availability, model validation, and the ability of predictive algorithms to perform across different feedstocks and reactor

configurations [172]. Consequently, future work should emphasize long-term field validation rather than relying solely on laboratory datasets.

Hydrogen integration and power-to-gas systems provide a promising pathway for increasing methane recovery from the carbon dioxide fraction of biogas and linking anaerobic digestion with variable renewable electricity. However, the additional electrolyzer, hydrogen-storage, and methanation infrastructure increases capital and energy requirements. Their commercial attractiveness is therefore strongly dependent on electricity prices, availability of surplus renewable electricity, carbon dioxide recovery efficiency, and the value of renewable methane [164]. These systems are more likely to become commercially attractive in regions with high renewable-electricity penetration and established gas infrastructure. Biochar and other emerging materials can improve anaerobic digestion by providing microbial attachment surfaces, adsorbing inhibitory compounds and potentially facilitating electron transfer. However, their performance varies with material characteristics, dosage, feedstock and reactor conditions [23,28]. Large-scale implementation also requires assessment of material production energy, cost, availability, durability, and environmental fate. These approaches therefore remain more appropriate as targeted process-enhancement strategies than as universally applicable solutions. Microbial electrolysis and other bioelectrochemical approaches have considerable scientific potential but remain less mature than conventional digestion and commercially established upgrading technologies. Their major barriers include electrode cost, electrical-energy requirements, reactor complexity, long-term stability, and limited evidence from continuous operation at commercial scale. Further pilot-scale studies are required to establish whether additional methane recovery can justify the associated capital and operating costs. Nanomaterial-assisted digestion represents an even earlier-stage pathway. Nanomaterials may enhance electron transfer or microbial activity, but potential toxicity, material recovery, environmental persistence, and digestate contamination require careful evaluation before widespread agricultural application.

Commercialization will depend on the development of low-cost, environmentally benign and recoverable materials together with long-term assessments of their fate in digestion systems.

Overall, the evidence suggests that the commercialization pathway is likely to be technology-specific rather than uniform. Advanced upgrading, process monitoring and selected reactor configurations are closest to widespread deployment, whereas hydrogen-integrated systems require favorable energy and gas-market conditions, and bioelectrochemical and nanomaterial-based approaches require further scale-up and environmental validation. This distinction is important because technological novelty should not be equated with technological readiness. Future research should therefore prioritize long-duration pilot demonstrations, standardized performance indicators, techno-economic assessment, life-cycle assessment, and field validation under realistic feedstock and operating conditions. Table 6 presents a comparative assessment of emerging biogas technologies in terms of readiness, limitations, and commercialization prospects.

7.10. Research Gaps and 10-Year Outlook

Despite substantial progress in feedstock utilization, process optimization, reactor development, biogas upgrading and energy recovery, several important knowledge, and implementation gaps remain. The evidence synthesized in this review indicates that the next stage of biogas development should move beyond demonstrating improved methane production under controlled conditions toward establishing reliable, scalable, economically viable, and environmentally sustainable performance under realistic operating conditions.

7.10.1. Research Gaps

Feedstock variability and long-term process stability remain major research priorities. Many

experimental investigations are conducted using relatively homogeneous substrates under controlled laboratory conditions, whereas full-scale digesters experience changes in feedstock composition, moisture content, organic loading, contaminants and seasonal availability.

Future research should therefore emphasize long-term continuous operation using realistic feedstock mixtures and should quantify how variations in substrate composition affect microbial stability, methane productivity, and digestate quality. Standardized reporting of feedstock characteristics, operating conditions, and methane-yield basis would also improve comparability among studies.

The mechanisms and interactions underlying inhibition require further investigation. Ammonia, volatile fatty acids, sulfide, heavy metals and salinity can occur simultaneously, yet many studies evaluate these stressors individually. Greater attention is therefore needed to interactions among inhibitors, microbial community structure, temperature, pH, and substrate composition. Future studies should combine biochemical measurements, microbial-community analysis and kinetic modelling to develop predictive indicators of inhibition and recovery under realistic operating conditions.

Scale-up and long-term validation represent another major gap. Several promising process-enhancement approaches have demonstrated improved performance at laboratory or pilot scale, but evidence from long-duration commercial operation remains limited. Future studies should report performance over sufficiently long periods to capture seasonal feedstock variation, process disturbances, equipment degradation and maintenance requirements. Pilot and commercial studies should also report standardized indicators such as methane productivity, methane recovery, net energy balance, energy consumption, methane leakage, CAPEX, and OPEX.

Table 6. Comparative assessment of emerging biogas technologies in terms of readiness, limitations, and commercialization prospects.

Technology	Current readiness	Main advantages	Major limitations	Commercialization prospects
Two-stage/temperature-phased AD	High–medium	Better process control, stability and potentially higher methane productivity	Higher capital cost and process complexity	High where increased productivity offsets additional cost
Advanced biogas upgrading	High	High methane purity; suitable for grid/transport applications	Energy demand, contaminant sensitivity and methane slip	High
AI/IoT monitoring and control	High–medium	Real-time monitoring, prediction and process optimization	Sensor reliability, data requirements and model transferability	High
Hydrogen/P2G integration	Medium	Converts biogenic CO ₂ to additional methane; integrates AD with renewable electricity	High CAPEX, electricity demand and infrastructure requirements	Medium–high in favourable energy markets
Biochar-assisted AD	Medium–low	Potential inhibition control, microbial support and process stabilization	Variable performance, material cost and environmental fate	Medium; application-specific
Microbial electrolysis/bioelectrochemical systems	Low–medium	Potential methane enhancement and energy recovery	Electrode cost, electricity requirement and scale-up uncertainty	Emerging/niche
Nanomaterial-assisted AD	Low	Potential catalytic and electron-transfer enhancement	Toxicity, recovery, persistence and cost	Low in near term

Note: Readiness categories are qualitative assessments based on the extent of demonstrated laboratory, pilot and commercial application in the literature reviewed; they are not formal numerical Technology Readiness Levels (TRLs).

Methane leakage requires more comprehensive measurement and integration into environmental assessment. Methane losses may occur during digestion, gas storage, upgrading, compression, combustion, and digestate management. However, measured emission data remain insufficiently consistent across technologies and geographical regions. Future research should therefore develop standardized measurement protocols and incorporate measured or technology-specific leakage factors into life-cycle assessments rather than relying exclusively on generic assumptions.

Techno-economic and life-cycle assessments also require greater methodological consistency. Differences in plant scale, system boundaries, feedstock costs, discount rates, energy prices, allocation procedures and assumptions about

methane leakage can produce substantially different economic and environmental results. Future studies should report CAPEX, OPEX, LCOE or equivalent cost indicators, NPV, IRR and payback period together with sensitivity and uncertainty analyses. Environmental assessments should similarly report functional units, system boundaries, allocation procedures and counterfactual scenarios clearly enough to permit meaningful comparison.

The geographical distribution of research is another important gap. Evidence from Europe, China, and other regions with established research and infrastructure is considerably stronger than evidence from many parts of sub-Saharan Africa and other developing regions. Future research should therefore give greater attention to locally available feedstocks, decentralized and

community-scale systems, local manufacturing, maintenance capacity, financing mechanisms and realistic energy-use pathways. This is particularly important because technology configurations that are economically attractive in developed biomethane markets may not be appropriate for regions lacking gas-grid infrastructure or access to long-term financing.

Digestate valorization and nutrient recovery also require greater integration into biogas-system assessment. Digestate is frequently treated as a secondary output even though it contains recoverable nitrogen, phosphorus, potassium and organic matter. Future research should evaluate nutrient-recovery technologies together with fertilizer-substitution benefits, storage emissions, contaminant risks and local agricultural requirements. Such integration could improve both the economic and environmental performance of biogas systems.

Finally, future research should increasingly evaluate anaerobic digestion as an integrated waste, energy, nutrient, and carbon-management system rather than as an isolated methane-production process. The most appropriate configuration will depend on feedstock characteristics, reactor conditions, energy demand, infrastructure, financing, policy support and environmental objectives. Consequently, future studies should combine biochemical performance, techno-economic analysis and life-cycle assessment within consistent system boundaries.

7.10.2. 10-Year Outlook

Over the next decade, biogas research is expected to shift progressively from isolated process improvements toward integrated, digitally monitored, low-emission and resource-recovery systems. In the near term, greater emphasis is likely to be placed on reliable process monitoring, methane-leak detection, improved reactor control, standardized performance assessment and optimization of established upgrading technologies. In the medium term, greater integration of nutrient recovery, digestate valorization, modular upgrading and combined techno-economic and life-cycle assessment should improve the sustainability and bankability of

biogas projects. By the latter part of the decade, the most competitive systems are likely to combine efficient anaerobic digestion with methane-loss minimization, renewable-energy integration, nutrient recovery, digital process control, and verified life-cycle environmental performance.

The principal research challenge over this period will therefore be to determine under which feedstock, technological, economic, and environmental conditions biogas systems can deliver reliable energy recovery with low life-cycle emissions and commercially acceptable costs. Progress should be measured not only by increases in methane yield, but also by improvements in net energy recovery, methane retention, economic return, resource recovery and greenhouse-gas mitigation.

8. Conclusion

Biogas production through anaerobic digestion has evolved from a primarily waste-treatment technology into a multifunctional renewable-energy and resource-recovery pathway. The evidence synthesized in this review demonstrates that improvements in feedstock utilization, co-digestion, pretreatment, reactor configuration, temperature management, inhibition control, process monitoring, and biogas upgrading can improve methane recovery and operational stability. However, the magnitude and consistency of these improvements depend strongly on feedstock composition, digestion conditions, reactor configuration, pretreatment intensity, microbial stability, and the methodological basis used to report methane performance. Consequently, methane yield alone is insufficient for determining the superiority of a biogas technology.

The review further demonstrates that the environmental and economic performance of biogas systems depends on factors extending beyond the digester itself. Methane leakage from digestion, storage, upgrading, combustion, and digestate management can substantially reduce climate benefits, while pretreatment, upgrading, transport, and digestate management may introduce additional energy demand and environmental burdens. Similarly, techno-economic performance is strongly influenced by

plant scale, feedstock logistics, capital requirements, financing conditions, energy markets, infrastructure, and policy incentives. Integrated techno-economic and life-cycle assessment is therefore essential for identifying configurations that provide acceptable economic returns together with genuine environmental benefits.

Technological maturity also varies considerably across the emerging pathways reviewed. Advanced digestion configurations, biogas upgrading and digital monitoring are relatively close to widespread deployment, whereas hydrogen-assisted methanation, biochar-assisted digestion, bioelectrochemical systems and nanomaterial-based approaches require different levels of further technical, economic or environmental validation. Technological novelty should therefore not be equated with commercial readiness. Long-duration pilot studies, standardized performance indicators, methane-leakage measurements, and transparent techno-economic and life-cycle assessments are required to establish whether laboratory-scale advances can deliver reliable benefits at commercial scale.

The review also highlights an important geographical dimension. Developed regions generally benefit from more established energy and gas infrastructure, organized feedstock supply chains, commercial financing, and supportive renewable-gas policies, whereas many developing regions face constraints related to financing, infrastructure, technical capacity, maintenance, feedstock collection, and policy consistency. Consequently, technology transfer should emphasize context-specific adaptation rather than direct replication of capital-intensive systems developed for mature biomethane markets. Decentralized and community-scale systems, local manufacturing, appropriate financing mechanisms, and resource-recovery applications may provide more suitable pathways in regions where centralized gas infrastructure is limited. Looking toward the next decade, the major research challenge is to move from isolated improvements in methane production toward integrated, reliable, low-emission, and resource-efficient biogas systems.

Priority areas include long-term validation under variable feedstock conditions, improved understanding of interacting inhibition mechanisms, standardized methane-leakage measurement, consistent techno-economic and life-cycle methodologies, digestate and nutrient valorization, digital process control, and stronger evidence from developing regions. Future biogas systems are likely to increasingly integrate methane production with upgrading, renewable-electricity utilization, nutrient recovery, digital monitoring, and carbon-management strategies. Overall, biogas should not be regarded as a universally optimal renewable-energy technology, but as a context-dependent component of circular energy systems whose effectiveness depends on the interaction of biochemical performance, technological maturity, environmental integrity, economic viability, and enabling infrastructure. Its long-term contribution to sustainable energy transitions will therefore depend not simply on increasing methane yield, but on maximizing net energy recovery, methane retention, resource recovery, economic value, and greenhouse-gas mitigation simultaneously.

Author's contribution

Anthony Chibuike Ohajianya: Conceptualization, methodology, formal analysis, writing—original draft, editing and validation; **Justin Chikezie Nnokwe:** Writing—review and validation; **Uchenna Sydney Mbamara:** Writing—review and validation; **Festus Uchenna Nwaneho:** Writing—review and validation; **Benjamin Okechukwu Okereke:** Writing—review and validation; **Ogechukwu Eucharia Okwueze:** Writing—review and validation. All authors have read and agreed to submit this manuscript.

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