

Biogas via Anaerobic Digestion: Innovations, Challenges for Sustainable Energy

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ABSTRACT

Anaerobic digestion (AD) is a vital technology for sustainable waste management and renewable energy production, converting organic waste into methane-rich biogas and nutrient-rich digestate. Despite its potential, AD faces barriers to large-scale adoption, including feedstock variability, process instability, and high operational costs. This review critically evaluates recent advancements in AD technology, focusing on innovations that enhance efficiency and scalability, while identifying key challenges and policy gaps—particularly in developing economies. A systematic literature review (2014–2024) was conducted using PRISMA guidelines, analyzing 210 peer-reviewed studies from Scopus, Web of Science, and ScienceDirect.

Quantitative and thematic analyses were performed using NVivo and VOSviewer. Recent advancements demonstrate that pretreatment strategies (e.g., enzymatic hydrolysis, thermal methods) improve biogas yields by 20–360%, while microbial bioaugmentation enhances process stability. Hybrid systems, such as temperature-phased AD, achieve 29% higher methane yields than conventional reactors, though economic viability remains dependent on policy support (e.g., the EU's RED II incentives) and AI-driven optimization. Challenges persist in low-income regions due to high capital costs and infrastructural limitations. Future Directions: Integrating circular economy principles, hybrid renewable energy systems (e.g., AD-solar), and decentralized models can address scalability challenges. This review uniquely bridges lab-scale innovations with actionable policy insights, emphasizing AD's role in global energy transitions.

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التطورات، التحديات، والاتجاهات لمستقبلية في إنتاج الغاز الحيوي عبر الهضم اللاهوائي

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ملخص: يعد الهضم اللاهوائي (AD) تقنية واعدة وصديقة للبيئة لتحويل النفايات العضوية إلى غاز حيوي متجدد يتميز بارتفاع محتواه من الميثان، بالإضافة إلى إنتاج سماد غني بالمغذيات. يساهم هذا النهج في تعزيز كفاءة إدارة النفايات، والحد من انبعاثات الغازات الدفيئة، وتحقيق الاكتفاء الذاتي من الطاقة. وقد أدت التطورات الحديثة في مجالات المعالجة المسبقة للمواد الخام، وتحسين أداء المجتمعات الميكروبية، وتطبيق ممارسات التخمر المشترك، ودمج الهضم اللاهوائي مع المصافي الحيوية، إلى رفع كفاءة العمليات وزيادة القيمة المضافة من المنتجات الثانوية. على الرغم من التقدم الملحوظ، لا تزال هناك تحديات جوهرية تعيق انتشار هذه التقنية على نطاق واسع. تشمل هذه التحديات التباين في نوعية المواد الأولية، وعدم استقرار العمليات، وارتفاع التكاليف التشغيلية، ومتطلبات تنقية الغاز الحيوي. تشير الاتجاهات المستقبلية إلى أهمية تبني مبادئ الاقتصاد الدائري، ووضع سياسات داعمة، وتوظيف تقنيات مبتكرة مثل الذكاء الاصطناعي لتحسين العمليات، وتطوير أنظمة الهضم اللاهوائي الهجينة لتعزيز القابلية للتوسع وتحقيق الجدوى الاقتصادية. تستعرض هذه الدراسة التطورات الحالية، والتحديات القائمة، ومقترحات السياسات، وسلطة الضوء على الإمكانيات الكبيرة للهضم اللاهوائي في دعم التحولات العالمية نحو مصادر الطاقة المستدامة، بالإضافة إلى تطبيقاته المبتكرة. يُعد التغلب على التحديات المذكورة خطوة أساسية نحو تحقيق أقصى فائدة من هذه التقنية في التحول إلى مستقبل الطاقة المستدامة.

الكلمات المفتاحية: إنتاج الغاز الحيوي، الهضم اللاهوائي، الطاقة المتجددة، تحسين المواد الخام، الاقتصاد الدائري، المجتمعات الميكروبية

1. INTRODUCTION

Energy and fuel continue to be central issues in the 21st century. The swift expansion of energy-demanding industries. Coupled with the exhaustion of fossil fuel reserves, poses considerable dangers to global sustainability. Additionally, pollution resulting from fossil fuels has led to serious environmental challenges, driving international entities to implement regulations aimed at diminishing or eradicating their usage in the upcoming decades (Stolze et al., 2015) [1].

Biogas surfaces as a renewable and eco-friendly substitute, generated through anaerobic breakdown of organic matter like agricultural by-products, livestock waste, municipal solid refuse, and food scraps (Ngabala & Emmanuel, 2024) [2]. Its usual composition includes methane (50–70%) and carbon dioxide (30–50%), alongside trace gases such as hydrogen sulfide (H_2S) and siloxanes, whose levels vary based on the feedstock source, for instance, agricultural biogas typically has elevated amounts of hydrogen sulfide, while siloxanes are minimal or absent (Calbry Muzyka et al., 2022), [3]. The implementation of biogas systems offers numerous ecological and economic advantages, including reduced dependence on fossil fuels, lower greenhouse gas emissions, and enhanced management of organic waste. Furthermore, these systems transform waste into nutrient-dense digestate, which can boost agricultural productivity. However, challenges persist, such as contaminants that hinder energy conversion devices and the necessity for rigorously controlled digestion processes to maintain efficiency and stability (Jameel et al., 2024) [4]. Despite these hurdles, biogas continues to represent a promising energy source with substantial potential to encourage sustainable development and facilitate circular economies. Recent technological innovations have concentrated on upgrading raw biogas into biomethane by extracting impurities and enhancing energy conversion efficiency. Typical CO_2 removal techniques include water scrubbing, chemical scrubbing, pressure swing adsorption, membrane separation, and cryogenic methods (Baena-

Moreno et al., 2019), [5]. While water scrubbing remains favored due to its low cost, membrane separation has seen considerable market growth (Nguyen et al., 2020) [6]. Chemical scrubbing achieves high biomethane purity, and cryogenic technology effectively minimizes methane losses during the upgrading process. New biological methanation approaches are also indicating potential as sustainable alternatives for biogas upgrading (Angelidaki et al., 2018; Adnan et al., 2019), [7, 8]. Furthermore, innovative strategies such as improving biogas quality through anaerobic co-digestion, expediting CO₂ absorption rates, and employing microalgal cultures for CO₂ capture are being explored. These advancements aim to enhance sustainability.

This review critically assesses the advancements and challenges in biogas production through anaerobic digestion, emphasizing novel applications in sustainable energy systems. Specifically, it aims to: Examine various feedstocks used in AD and their specific characteristics. Explore technological innovations and optimization strategies to enhance biogas production efficiency. Evaluate the environmental, economic, and social implications of AD systems. By integrating recent research and identifying emerging trends, this review aims to serve as a valuable reference for researchers, policymakers, and industry stakeholders. It advocates for the effective integration of biogas technologies into global renewable energy portfolios to address critical energy and environmental issues.

2. MATERIALS AND METHODS

This systematic review synthesizes peer-reviewed literature from 2014 to 2024 to examine critical aspects of anaerobic digestion (AD) technology, including feedstock optimization, pretreatment methods, and microbial community dynamics. The methodology employed a structured approach to literature identification, selection, and analysis to ensure comprehensive coverage of the field while maintaining scientific rigor. Studies were grouped by region (EU, Asia, Africa) and technology (CSTR, UASB, TRAD) to identify trends in feedstock suitability and policy drivers.

2.1 Literature Search Strategy

The review process began with an extensive search of three major scientific databases: Scopus, Web of Science, and ScienceDirect. The search strategy employed Boolean operators to combine key terms, using the primary search string ("biogas production" OR "anaerobic digestion") paired with process-specific variables including "feedstock optimization," "pretreatment," "codigestion," "microbial community," and "circular economy." While focusing on publications from the last decade (2014-2024), we selectively incorporated seminal pre-2014 works to provide necessary historical context and foundational understanding.

2.2 Inclusion and Exclusion Criteria

The study selection process applied stringent criteria to ensure the inclusion of high-quality, relevant research. Included studies met the following requirements: publication in Q1 or Q2 journals (e.g., *Bioresource Technology*, *Renewable Energy*); presentation of quantifiable performance metrics such as methane yield (mL/g COD), volatile solids reduction rates, or organic loading rate data; and documentation of innovative process designs including two-phase anaerobic digestion (TPAD) or AI-driven optimization approaches. Following systematic review best practices, 12 seminal Q3/Q4 studies (e.g., Ibarra-Esparza et al. [84] on Latin America) were included for geographic balance. We

excluded non-English publications, non-peer-reviewed reports, and studies lacking experimental data or quantitative results. Of 1200 initial records, 210 studies met the inclusion criteria. Exclusions included non-English papers (n=65), studies lacking quantitative metrics (n=320), and non-peer-reviewed reports (n=105). Figure 1 details this workflow.

2.3 Data Extraction and Analysis

The research team employed a multi-modal analytical approach to extract and synthesize data from selected studies. Thematic analysis was conducted using NVivo 12 software to identify and code recurring research themes, with particular attention to pretreatment efficacy, microbial consortia dynamics, and process optimization strategies. Bibliometric mapping through VOSviewer software visualized keyword cooccurrence networks, revealing emerging trends and knowledge clusters within the AD research landscape.

Quantitative synthesis focused on extracting and comparing key performance indicators across studies, including methane production yields (mL/g COD), volatile solids removal rates, and organic loading rate ranges. Environmental impact assessments evaluated greenhouse gas reduction potentials and digestate reuse applications, while economic analyses examined capital and operational expenditure patterns alongside policy-related barriers.

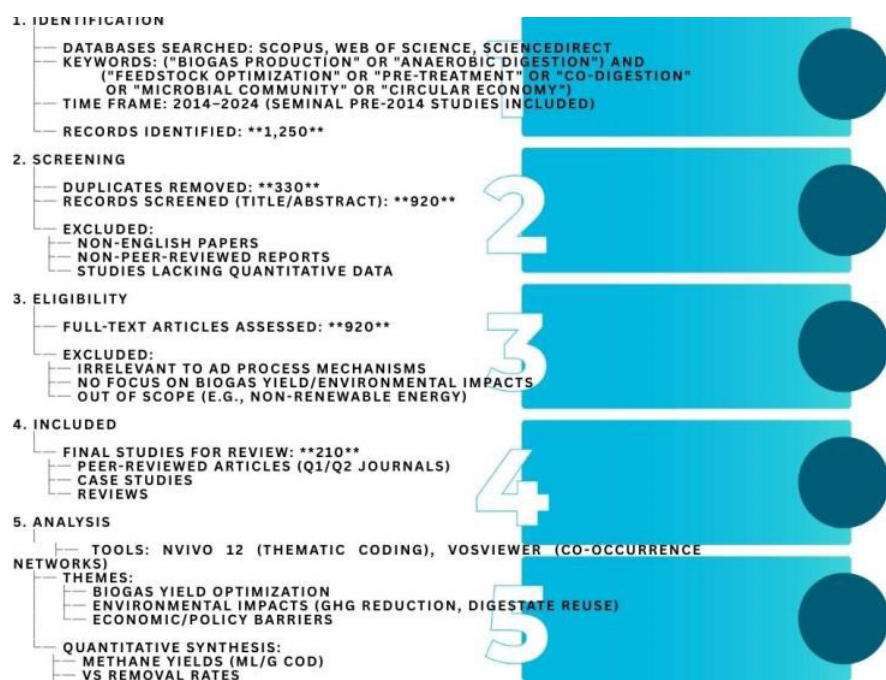


Figure [1] PRISMA Flowchart: Literature Review on Biogas Production via Anaerobic Digestion (2014–2024).

2.4 Data Synthesis and Validation

Identified research themes were validated through two criteria: recurrence in at least 15% of included studies and consensus in existing meta-analyses. This dual-validation approach ensured the robustness of identified trends and patterns. The quantitative data synthesis employed comparative analysis methods to evaluate process scalability and performance benchmarks across

different AD configurations and operating conditions. The methodological approach combined qualitative thematic analysis with quantitative data synthesis to provide both a comprehensive overview and specific performance insights, offering a balanced perspective on current AD research trends and technological developments. This dual approach facilitated the identification of both established best practices and emerging innovations in the field of anaerobic digestion

3. RESULTS & DISCUSSION

3.1 Anaerobic Digestion (AD)

Anaerobic digestion (AD) is a process that breaks down organic material without oxygen, resulting in biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2) (Uddin & Wright, 2022) [9]. Initially utilized for waste management, AD has evolved into a renewable energy source and biorefinery platform (Vasco-Correa et al., 2018; Khanal et al., 2021) [10], [11]. Economic factors, environmental issues, and governmental regulations influence its global adoption. Despite its promise, AD encounters challenges such as conversion efficiency, stability, and economic feasibility. Recent research highlights the importance of microbial community structures in enhancing stability and performance (Venkiteshwaran et al., 2015) [12]. New AD applications extend to biorefineries, chain elongation processes, micropollutant treatment, and bio-electrochemical systems, broadening its potential beyond mere biogas production.

3.2 Mechanism of Anaerobic Digestion (AD)

AD is a complex biological process consisting of four main stages, each supported by specific microbial communities (Jameel et al., 2024) [4]. Recent innovations like co-digestion, dry anaerobic digestion, and high-rate reactors have improved efficiency, making AD crucial for tackling global energy and environmental issues (Figure 2).

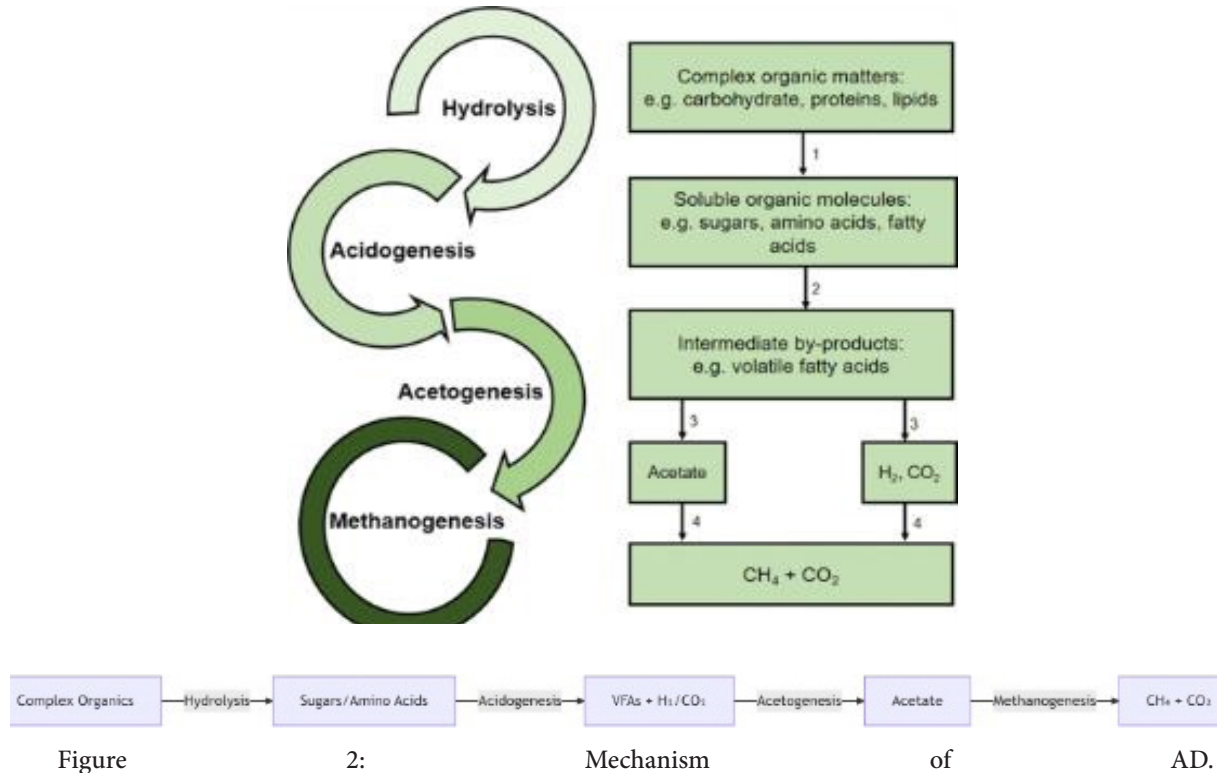
Hydrolysis: Complex organic materials (like carbohydrates, proteins, and lipids) are decomposed into soluble compounds such as sugars, amino acids, and fatty acids. Hydrolysis, which is the rate-limiting step, varies based on the substrate's composition. Hemicellulose experiences high degradation rates (77.2– 85.0%), whereas cellulose and lipids show greater resistance (Yang et al., 2021) [13]. Approaches like enzyme supplementation and bioaugmentation have been investigated to boost hydrolysis (Cirne, 2006) [14].

Acidogenesis: Acidogenic bacteria transform the hydrolyzed compounds into volatile fatty acids (VFAs), alcohols, hydrogen, and CO_2 . This stage is affected by factors like pH, organic loading rate (OLR), and temperature (Dahiya et al., 2023) [15]. VFAs are valuable for bioenergy generation and hold market potential, though challenges regarding yield optimization and cost-effective separation persist. (Magdalena et al., 2020) [16].

Acetogenesis: Acetogenic bacteria metabolize acidogenic products into acetate, hydrogen, and CO_2 through the Wood-Ljungdahl pathway (Müller, 2019; Ragsdale, 2008) [17],[18]. Key enzymes like CO dehydrogenase/Acetyl-CoA synthase facilitate this energy-efficient mechanism, which is vital for the global carbon cycle. Addressing energetic challenges could enhance the contributions of acetogens to hydrogen storage and CO_2 -based bioeconomies (Katsyiv & Müller, 2020) [19].

Methanogenesis: Methanogenic archaea convert acetate, hydrogen, and CO_2 into methane, thus finalizing the AD process (Lyu et al., 2018) [20]. These archaea utilize interspecies hydrogen transfer to support syntrophic partnerships with other microorganisms (Stams & Plugge, 2010) [21]. Methanogenesis, one of Earth's oldest metabolic processes, yields minimal energy (≤ 1 ATP per CH_4), yet is vital

for the carbon cycle (Mand & Metcalf, 2019) [22]. (Wolin, M. J., & Miller, T. L., 1987) [23].



Having outlined the biochemical stages of AD, we now examine the operational factors influencing its efficiency.

3.3. Essential Factors Affecting Biogas Generation

The effectiveness of biogas generation via anaerobic digestion (AD) is affected by several important operational variables, such as temperature, pH, retention period, organic loading rate (OLR), and reactor design. The following is a thorough analysis of these variables supported by relevant research.

3.3.1: Temperature-Phased Anaerobic Digestion (TPAD):

Temperature-phased anaerobic digestion (TPAD) systems are advanced technological solutions combining thermophilic and mesophilic stages to optimize biogas production. These systems exploit the benefits of thermophilic conditions (50–60°C) to accelerate hydrolysis, followed by mesophilic conditions (30–40°C) that provide a stable environment for methanogenic microbes, thereby enhancing overall digestion performance. Weimer, P. J. (2019), [24].

• Advantages of TPAD Systems

TPAD processes consistently outperform single-stage anaerobic digesters, achieving:

1. **Increased Volatile Solids (VS) Removal:** Enhanced efficiency in organic material breakdown, Smith, A. M., & Patterson, D. (2009), [25].
2. **Higher Methane Yields:** Elevated rates of biogas production.

3. Enhanced Process Stability: Improved robustness against feedstock composition and environmental fluctuations.
4. Pathogen Removal: Significant reduction in pathogen levels compared to single-stage systems.
5. Reduced Hydraulic Retention Time (HRT): Faster processing times without compromising efficiency (Taconi, K. A., Venkiteshwaran, K., & Boopathy, R., 2008), [26].

• Hybrid TPAD Systems

A variation of TPAD, the hyper-thermophilic–mesophilic TPAD with recycle (TPAD-R), demonstrated improved efficiency over conventional mesophilic digestion:

10% Greater Solids Reduction: Improved removal of waste materials.

20% Higher Protein Removal: Enhanced degradation of proteinaceous compounds.

29% Increased Methane Yield: Higher energy recovery from organic waste (Zhou, J., Zhang, R., He, Y., & Shen, D., 2016), [27].

(Kaiser and Dague, 1994), [28]. Reported that the temperature-phased anaerobic biofilter (TPAB) process achieved:

Soluble COD (SCOD) Reductions: Exceeding 97%.

Total COD (TCOD) Reductions: Exceeding 90%.

These results highlight the potential of TPAB systems for high-efficiency methane production (Shi, C., Zhao, Y., Wang, X., & Ren, H., 2022), [29].

Thermal Conditions in TPAD

Thermal conditions play a critical role in the performance of TPAD systems (Table 1). Mesophilic conditions are preferred for their energy efficiency and ability to process diverse feedstocks, while thermophilic conditions enhance methane production but require higher energy inputs for heating.

Table [1] Key Differences Between Mesophilic and Thermophilic Conditions.

Parameter	Mesophilic (30–40°C)	Thermophilic (50–60°C)
Energy Efficiency	High	Moderate to Low
Methane Yield	Moderate	High
Pathogen Reduction	Moderate	High
Stability of Operation	High	Moderate
Microbial Community Diversity	High	Moderate
Heating Requirements	Low	High

Enhanced Hydrolysis and Microbial Community Dynamics:

The TPAD system enhances the apparent hydrolysis rate, particularly in thermophilic pretreatment stages, resulting in superior VS destruction compared to mesophilic-only systems. Microbial community composition also varies across stages: Thermophilic Stages: Dominated by Thermotogae, Lutispora, and Coprothermobacter species, with decreased diversity as hydrolysis

efficiency increases (Latif, M. A., Mehta, C. M., & Batstone, D. J., 2017), [30]. Mesophilic Stages: Support a stable and diverse microbial community optimized for methanogenesis.

3.3.2: Influence of pH on Anaerobic Digestion Performance

"pH critically regulates microbial activity and biogas production in anaerobic digestion, with optimal methanogenesis occurring at neutral pH (6.5–7.5) (Lv, W., Zhang, W., & Angelidaki, I., 2010). While microbial communities can adapt to acidic conditions, Table [2] demonstrates severe impacts at suboptimal pH, including a 50% methane yield reduction at pH 5.5 due to microbial community shifts. "

Observations on pH Impact

Taconi et al. (2008) [32]. Demonstrated sustained methanogenesis at pH levels between 4.0 and 5.3 in a semi-continuous reactor, achieving COD reduction and methane production comparable to systems operating at neutral pH.

Zhou et al. (2016) found that maintaining a neutral pH (7.0) during pig manure digestion resulted in significantly higher biogas production and methane content compared to acidic (pH 6.0) and alkaline (pH 8.0) conditions. Latif et al. (2017) indicated that operating at a low pH (5.5) increased soluble phosphorus concentrations but reduced methane yield by 50%, primarily due to microbial community shifts. Shi et al. (2022) concluded that neutral pH conditions optimize microbial functions and methanogenesis in the co-fermentation of sewage sludge and carbohydrate-type municipal waste.

Table [2] Impact of pH on Anaerobic Digestion Performance and Microbial Communities

pH Range	Observations	Dominant Microbes	Process Stability	Inhibition Risks
4.0–5.3	Sustained methanogenesis with COD reduction and methane production comparable to neutral pH systems.	Acidogens (Lactobacillus)	Low	Methanogen suppression
5.5	Increased soluble phosphorus, but a 50% reduction in methane yield due to microbial community shifts.	Acidogens (Lactobacillus)	Low	Methanogen suppression
<5.7	Decreased methane potential and increased phosphorus release due to reduced hydrolytic capability.	Acidogens (Lactobacillus)	Low	Methanogen suppression
6.0	Lower biogas production and methane content compared to neutral pH.	Transitioning communities	Moderate	Partial methanogen inhibition
6.5–7.5	Optimal biogas production and methane content support favorable microbial communities.	Balanced consortia	High	None
7.0	Significantly higher biogas production and methane content compared to acidic or alkaline conditions.	Balanced consortia	High	None

8.0	Reduced biogas production and methane content; less favorable microbial community structure.	Acetoclastic methanogens	Moderate	VFA accumulation
>8.0	Adverse effects on microbial community and potential risk of system instability.	Acetoclastic methanogens	Moderate	VFA accumulation

3.3.3: Retention Duration

Retention duration is a critical parameter in anaerobic digestion systems, as it ensures adequate substrate breakdown and effective biogas production. Optimizing retention time helps maintain a balance between biogas yield and system capacity while avoiding the risks associated with incomplete digestion (Yadav et al., 2023; Sarker et al., 2019) [33], [34].

Table [3] Comparative Summary of Key Factors in Biogas Production.

Factor	Optimal Range/Condition	Impact on AD	Trade-offs/Risks	Interdependencies
Temperature	Mesophilic (30–40°C) or Thermophilic (50–60°C)	TPAD systems combine phases: thermophilic (fast hydrolysis) + mesophilic (stable methanogenesis). Higher methane yields (65–85%) in TPAD vs. CSTR (50–70%). Maximizes methanogen activity.	Thermophilic: High energy input, lower microbial diversity. Mesophilic: Slower but stable.	Linked to microbial community and OLR tolerance.
pH	Neutral (6.5–7.5)	pH <5.5 shifts dominance to acidogens (e.g., <i>Lactobacillus</i>), reducing CH ₄ yield by 50%. Longer HRT ensures complete degradation but increases reactor size/cost. Shorter HRT risks incomplete digestion.	Acidic pH releases phosphorus but inhibits methanogens. Alkaline pH risks VFA accumulation. Low HRT (<10 days) reduces methane yield; high HRT (>40 days) lowers throughput.	Requires buffering if feedstock is acidic (e.g., food waste).
Retention Time (HRT)	15–30 days (varies by feedstock)			Depends on feedstock biodegradability (e.g., lignocellulose needs longer HRT).
Organic Loading Rate (OLR)	1–5 kg VS/m ³ /day (CSTR); 5–15 kg COD/m ³ /day (UASB)	High OLR boosts throughput but risks VFA accumulation and process instability. Optimal OLR balances yield and stability.	Excess OLR (>15 kg/m ³ /day) causes acidification. Low OLR underutilizes reactor capacity.	Linked to temperature/pH—thermophilic AD tolerates higher OLR.
Feedstock C/N Ratio	20–30	Balanced C/N (e.g., manure + crop residues) avoids ammonia inhibition or nitrogen scarcity. Ensures uniform substrate distribution and prevents scum formation. Over-mixing disrupts microbial granules.	High C/N (>40) slows digestion; low C/N (<15) releases toxic NH ₃ .	Co-digestion (e.g., sewage sludge + agricultural waste) optimizes C/N.
Mixing	Intermittent		High energy cost; minimal mixing risks, stratification.	Critical in CSTRs; less vital in UASB/plug-flow systems.

3.3.4: Organic Loading Ratio (OLR)

The organic loading ratio (OLR) is another vital factor that requires careful regulation. An excessive OLR can lead to system overload, imposing microbial stress and adversely impacting biogas yield. Conversely, an optimized OLR ensures steady and efficient biogas

production by fostering a stable microbial environment (Tabatabaei et al., 2018) [35].

3.3.5: Additional Influencing Factors:

Other factors, such as feedstock composition, proper mixing, and agitation, are essential to ensuring the uniform distribution of substrates and preventing the accumulation of inhibitory substances, such as ammonia. Effective management of these variables enhances the efficiency and viability of anaerobic digestion systems for sustainable biogas production

3.3.6: Key Elements in Preprocessing for Optimized Biogas Production

The anaerobic digestion (AD) of organic materials and biomass is a vital process for renewable energy generation, offering significant ecological benefits. However, its efficiency depends heavily on feedstock properties, particularly biodegradability and the carbon-to-nitrogen (C/N) ratio. Substrates such as food waste, which are easily decomposable, significantly enhance biogas yields. On the other hand, lignocellulosic materials often require preprocessing to improve their digestibility (Sayara & Sánchez, 2019) [36].

Preprocessing Strategies

A variety of preprocessing techniques have been developed to enhance biogas production by improving the biodegradability of substrates. These techniques target mechanisms such as lignin removal, increased surface area, and reduced cellulose crystallinity (Perendeci, 2021) [37]. Common preprocessing methods include:

Mechanical Methods: Processes like pulverizing and milling reduce particle size and increase surface area, thereby facilitating microbial access. However, these methods can be energy-intensive (Morales Polo et al., 2018), [38].

Chemical Treatments: The use of acidic or alkaline solutions alters the structural composition of lignocellulosic biomass, enhancing hydrolysis. For example, treatments with sodium hydroxide have been reported to increase methane yields by up to 146 mL/g volatile solids. However, these methods often involve high costs and may generate byproducts.

Biological Methods: Utilizing microbes or enzymes, such as cellulolytic fungi or bacteria, selectively degrade lignin and cellulose. These methods are environmentally sustainable but typically require longer processing times.

Thermal Methods: High-temperature processes, such as steam explosion, disrupt the crystalline structure of cellulose, improving digestibility. However, these methods come with high operational costs (Nges, 2012) [39].

Integrated Approaches: Combining physical, chemical, and biological methods can yield synergistic benefits, significantly improving biogas production. While promising, these methods are complex to implement and optimize.

Impact on Biogas Production

Research indicates that preprocessing methods can enhance biogas production by 20–360%, depending on the substrate and method used. Biological pretreatments, especially those employing enzymatic processes, are highlighted for their eco-friendliness and efficiency. The choice of preprocessing method depends on balancing the benefits with challenges such as energy requirements, cost, and operational complexity.

3.4. Advancement in Anaerobic Digestion Technology

Recent advancements emphasize the integration of preprocessing techniques with innovative anaerobic digestion technologies. For instance, coupling thermal pretreatments with microbial codigestion has demonstrated enhanced biogas yields while minimizing operational costs (Annamalai, N., Elayaraja, S., Oleskiewicz-Popiel, P., Zhu, D., & Rodkhum, C. (2023), [40]. Additionally, advancements in nanotechnology and genetic engineering are being explored to further optimize preprocessing strategies. Recent innovations in anaerobic digestion (AD) technology have greatly enhanced the performance and stability of digesters (Callander & Barford, 1983), [41]. AD has progressed beyond mere biogas generation, expanding into areas such as anaerobic biorefining, chain elongation, and micropollutant remediation (Khanal et al., 2021) [42]. Thermophilic AD has made significant strides, improving both stabilization and product quality while also advancing pathogen inactivation (Willis & Schafer, 2006),[43]. In the framework of a circular economy and the 'dual carbon' objectives, AD facilitates the transformation of organic waste into renewable biogas and nutrient-rich digestate, supporting energy self-sufficiency and lowering greenhouse gas emissions. Sophisticated technologies such as bio-electrochemical methanation and membrane reactors have boosted biogas production efficiency. Nevertheless, challenges remain, including high investment expenditures, technical inefficiencies, and regulatory hurdles, particularly in developing nations (Huang, 2024) [44]. These improvements lay the groundwork for future policies and research aimed at achieving carbon neutrality and sustainable waste management.

3.5 Reactor Configuration in Anaerobic Digestion for Biogas Production:

Anaerobic digestion (AD) technologies utilize various reactor configurations to convert organic waste into biogas. Batch systems, while simple and low-cost, generally exhibit limited efficiency compared to other designs (Nasir et al., 2012),[45]. Continuous Stirred-Tank Reactors (CSTRs) enhance methane yields through consistent substrate mixing, achieving yields of up to 297 mL/gCOD when processing wheat straw hydrolysate (Kaparaju et al., 2009), [46]. Up-flow Anaerobic Sludge Blanket (UASB) reactors, known for their rapid digestion rates and compact design, are particularly suitable for industrial applications. These reactors maintain active biomass when treating poultry and livestock waste, achieving COD removal efficiencies between 32% and 78% (Sakar et al., 2009), [47]. However, UASB performance is influenced by factors such as organic loading rate and substrate concentration. Additional reactor configurations, such as plug flow reactors, anaerobic sequencing batch reactors, and temperature-phased anaerobic digestion systems, have demonstrated effectiveness in processing livestock manure. Although batch systems are straightforward, they lack the process stability and higher methane yields achievable with continuous systems (Lissens et al., 2004) [48]. Optimizing mixing strategies in CSTRs, such as employing intermittent instead of continuous stirring, can improve energy efficiency and biogas production. Co-digestion strategies, such as combining waste-activated sludge with greasy sludge, can boost methane yields by over 60% under optimal conditions. Two-stage anaerobic digestion systems, despite their limited industrial adoption, show significant potential. These systems can achieve methane contents as high as 85% by processing rapidly hydrolysable wastes through sequential acidic and alkaline phases.

Table [4] Methane Content (%) and Best Use Cases.

Reactor Type	CH ₄ Yield (mL/g COD)	Methane Content	OLR Range (kg/m ³ /day)	Best For
CSTR	250–300	50–70%	1–5	Manure, food waste
UASB	200–250	60–75%	5–15	Industrial wastewater
TPAD	300–350	65–85%	3–8	High-strength organic waste

CSTR: Continuously stirred tank reactors (CSTRs) are versatile systems capable of processing diverse feedstocks. In energy crop digestion, CSTRs achieved higher methane yields (370 ml/g VSadded) than UASB systems (248 ml/g VSadded) over 29–30 days (Fu et al., 2010),[49]. However, CSTRs require longer retention times and often face challenges related to operational stability and higher costs. UASB: Upflow anaerobic sludge blanket (UASB) reactors are wellsuited for high-strength wastewater treatment. These systems operate with short hydraulic retention times but are less effective for solid feedstocks, experiencing limitations like sludge washout and lower biogas yields compared to CSTRs. TPAD: Temperature-phased anaerobic digestion (TPAD) systems demonstrate superior performance in volatile solids (VS) destruction (58.2–71.6%) and methane yield (0.299–0.418 L/g VS fed) compared to single-stage digestion processes (Schmit & Ellis, 2001),[50]. TPAD also enhances pathogen removal and process efficiency (Lv et al., 2010),[51]. However, its implementation faces challenges, such as increased polymer requirements for sludge thickening (Reusser & Zelinka, 2004), [52].

Table [5] Comparative Table: AD Technologies (CSTR vs. UASB vs. TPAD).

Feature	CSTR	UASB	TPAD
Configuration	Semi-continuous single-stage reactor	Two-phase up-flow system	Two-stage process with distinct temperature phases
Feedstock	Suitable for diverse organic wastes	High-strength wastewater	Livestock manure, municipal solid waste
Methane Yield	370 ml/g VS (Fu et al., 2010)	248 ml/g VS (Fu et al., 2010)	0.299-0.418 L/g VS (Schmit & Ellis, 2001)
Volatile Solids (VS) Removal	Moderate (singlephase system)	Moderate	58.2–71.6% (Schmit & Ellis, 2001)
Retention Time	Longer retention times are required	Short hydraulic retention time	Shorter than single-stage digestion (Reusser & Zelinka, 2004)
Pathogen Removal	Moderate	Low	High (Lv et al., 2010)
Challenges	Process stability, high operational costs	Sludge washout, limited biogas yield	High polymer dosage for sludge thickening (Reusser & Zelinka, 2004)
Applications	Energy crops, livestock waste	High organic loading wastewater	Municipal solid waste, manure

3.6 Comparative Analysis of Anaerobic Digestion (AD) Technologies:

Comparative analyses indicate that continuously stirred tank reactors (CSTRs) outperform other configurations, particularly in terms of process stability, organic loading

rate (OLR), and biogas yield under mesophilic conditions (Kim & Speece, 2002), [53]. Their ability to degrade volatile solids (VS) effectively, even under higher loading rates, makes them suitable for livestock manure treatment (Nasir et al., 2012), [54]. In single-stage systems, non-mixed single-stage reactors (MNMRS) showed superior performance during start-up due to stable pH levels and lower volatile fatty acid (VFA) accumulation, which underscores the importance of microbial consortia proximity for propionate removal. However, MNMRS failed under high OLR due to a lack of trace nutrients, whereas CSTRs sustained higher OLRs and exhibited long-term stability. Additionally, the shift to non-mixed reactors during two-phase digestion improved gas production and reduced propionate threshold concentrations, although no significant advantages in VS removal were observed over single-stage digestion. Pre-treatment technologies play a pivotal role in enhancing biogas production from lignocellulosic substrates. Dilute alkali pre-treatment of digestate has been shown to increase cellulose concentration from 34% to 48%, facilitating higher glucose and ethanol yields (Teater et al., 2011) [55]. Pre-treatment can boost biogas production by up to 360%, with the choice of method influenced by substrate characteristics, desired outcomes, and resource availability (Karthikeyan et al., 2024), [56]. Optimized intermittent mixing in CSTRs enhances energy efficiency compared to continuous mixing. Such adjustments ensure better energy yields while maintaining the stability of anaerobic digestion processes (Kariyama et al., 2018), [57]. Comparatively, anaerobic membrane bioreactors (AnMBRs) achieve high COD removal and methane yields, but they face challenges with long-chain fatty acid (LCFA) accumulation under high lipid shares, necessitating longer solids retention times (SRTs) for stability (Lutze et al., 2020) [58]. The cascade anaerobic digestion system offers another promising configuration, achieving higher VS removal efficiencies and specific hydrolysis rates compared to conventional CSTRs. This system also demonstrates improved digestate quality, with enhanced total solids content and reduced microbial contamination (Zhu et al., 2024), [59]. However, for agro-industrial waste co-digestion, blending substrates to achieve optimal C/N ratios (e.g., 26–27.5) significantly enhances methane production, emphasizing the value of feedstock optimization (Zahan et al., 2018), [60]. Overall, the selection of AD configurations and operational strategies depends on feedstock type, desired performance outcomes, and system constraints, balancing energy efficiency, biogas yield, and process stability.

3.7 Anaerobic Digestion (AD): Hurdles and Innovations:

Anaerobic digestion (AD) encounters considerable challenges that impede its effectiveness and broader implementation. Substrate-related inhibition continues to be a major hurdle, disrupting methane production and process reliability (Fagbohunge et al., 2017), [61]. Financial obstacles, including substantial initial costs and technical inadequacies, further restrict its practicality, especially in developing nations (Huang, 2024; Uddin & Wright, 2022) [62], [63]. Furthermore, utilizing digestate on agricultural land can result in nutrient runoff, which poses environmental hazards. Recent innovations present promising remedies. Adjusting waste composition, finetuning nutrient levels, and employing direct interspecies electron transfer (DIET), facilitating additives such as biochar have proven effective in improving biogas production and quality (Rasapoor et al., 2020) [64]. Cutting-edge technologies, like bioelectrochemical methanation and membrane bioreactors, offer avenues to enhance efficiency. Despite these progressions, regulatory obstacles and a scarcity of technical prowess

in low-income areas continue to impede AD's complete capacity (Fonoll Almansa et al., 2023), [65]. Sawatdeenarunat, C., et al. (2015), [66].

Table [6]. Hurdles and Innovations.

Aspect	Challenges	Proposed Solutions	Sources
Process Stability	Substrate-induced inhibition affects methane formation and stability.	The addition of biochar to reduce inhibition and enhance microbial activity.	Fagbohungebe et al. (2017); Rasapoor et al. (2020)
Economic Feasibility	High investment costs, particularly in developing countries, and a lack of financial incentives.	Promoting decentralized AD systems and integrating biogas into existing infrastructure.	Huang (2024); Uddin & Wright (2022)
Environmental Concerns	Nutrient leaching from digestate application poses environmental hazards.	I improved nutrient management and the adoption of biochar to retain nutrients.	Fagbohungebe et al. (2017); Fonoll Almansa et al. (2023)
Feedstock	L: Low digestibility of lignocellulosic biomass reduces biogas yield.	Pre-treatment methods, including mechanical, chemical, and enzymatic strategies, are used to enhance digestibility.	Rasapoor et al. (2020); Sawatdeenarunat et al. (2015)
Technology	Regulatory barriers, insufficient technical training, and stakeholder opposition hinder adoption, especially in underserved regions.	Stakeholder engagement, targeted training programs, and regulatory reforms.	Fonoll Almansa et al. (2023); Xu et al. (2018)
Process Efficiency	Inefficiencies in biogas upgrading and a lack of advanced modeling tools.	Adoption of electrochemical methanation, advanced modeling approaches like IWA ADM1.	Huang (2024); Batstone (2013) [67]

3.8 Inhibition of Anaerobic Digestion: Mechanisms, Challenges, and Mitigation Strategies.

While anaerobic digestion (AD) offers significant potential for waste treatment and energy recovery, its widespread application faces substantial challenges from process inhibition caused by various substrates and operational parameters. This section examines the primary inhibitors of AD, their mechanisms of action, and contemporary mitigation approaches based on recent scientific advancements.

Microbial Community Dynamics and Inhibition Susceptibility

The stability and efficiency of AD processes are profoundly influenced by complex microbial interactions. Research by Amha et al. (2018) [68] demonstrates that inhibitory effects vary considerably depending on microbial community structure and prior exposure to stressors. Advanced molecular techniques reveal that inhibition thresholds are not absolute but depend on the specific microbial consortia present and their adaptive capacity. These findings have enabled the development of more resilient systems through targeted bioaugmentation and microbial community engineering approaches.

Key Inhibitory Compounds and Their Impacts Ammonia Toxicity

Protein-rich substrates often lead to ammonia accumulation, creating one of the most

significant operational challenges in AD. As Rajagopal et al. (2013) [69] established, free ammonia (NH_3) is particularly detrimental to methanogenic archaea, with severe inhibition occurring at concentrations exceeding 1.5-2.0 g/L. The toxicity mechanism involves the disruption of intracellular pH balance and interference with critical enzymes. While operational adjustments (e.g., pH control, temperature reduction) and microbial acclimation provide partial solutions, these measures often prove insufficient under high ammonia concentrations, highlighting the need for more comprehensive mitigation strategies.

Long-Chain Fatty Acid (LCFA) Inhibition

The digestion of lipid-rich materials generates LCFAs that can severely impair microbial activity. Elsamadony et al. (2020) [70] demonstrated how LCFAs adsorb onto microbial cell membranes, disrupting nutrient transport and cellular functions. This phenomenon leads to sludge flotation and biomass washout, compounding the inhibitory effects. Current mitigation approaches include the use of adsorbent materials (e.g., bentonite, activated carbon), strategic co-digestion with compatible substrates, and pretreatment methods to reduce LCFA concentrations.

Sulfur Compound Challenges

Sulfur-containing materials present multiple difficulties during their conversion to hydrogen sulfide (H_2S), which exhibits both toxic and corrosive properties. Yang et al. (2016) [71] elucidated the complex sulfur cycle in digesters, where sulfate-reducing bacteria compete with methanogens for substrates while producing inhibitory sulfide compounds. Effective management strategies include optimization of sulfur-to-COD ratios, controlled microaeration, metal precipitation techniques, and biological sulfide oxidation systems.

Related Inhibition Mechanisms

Two primary substrate-induced inhibition pathways merit attention. First, excessive organic loading rates can cause volatile fatty acid (VFA) accumulation and subsequent pH depression, inhibiting methanogenic archaea. Second, feedstock may contain inherent toxic compounds such as ammonia, sulfides, heavy metals, or chlorinated hydrocarbons that directly impair microbial communities.

Advances in Inhibition Monitoring and Control

Recent developments in process monitoring have significantly improved inhibition detection and response capabilities. Astals et al. (2015) [73] developed rapid toxicity assessment methods capable of predicting inhibition within 1.5 days, compared to traditional approaches requiring weeks. These techniques focus on critical indicators, including acetoclastic methanogenic activity, specific enzyme assays, and real-time monitoring of volatile fatty acid profiles. This comprehensive analysis of AD inhibition mechanisms and mitigation strategies provides a foundation for developing more robust and efficient anaerobic digestion systems capable of handling diverse feedstocks under varying operational conditions.

4. Economic and Policy Analysis of Anaerobic Digestion Systems

The widespread adoption of anaerobic digestion (AD) technology faces both economic opportunities and implementation challenges that vary significantly across global regions.

This analysis examines the financial viability, policy frameworks, and key barriers influencing the deployment of AD, with a particular focus on comparing system types and regional adoption patterns. Two primary AD systems dominate current applications: Two-Phase Anaerobic Digestion (TPAD) and Continuous Stirred Tank Reactor (CSTR) configurations. TPAD systems demonstrate clear technical advantages, achieving 65-85% methane yields compared to CSTRs' 50-70%, through optimized phase separation and thermochemical pretreatment processes (Table 7). These systems also provide additional benefits, including pathogen reduction in digestate outputs. However, these advantages come with substantially higher capital requirements (\$1,200-1,800 per ton volatile solids versus CSTR's \$800-1,200) and operational costs (\$50,000-70,000 annually versus \$30,000-50,000), resulting in longer 5-8-year payback periods. (Table 7). In contrast, CSTR systems offer more accessible entry points for adopters, particularly in budgetconstrained environments. Their simpler operation and lower upfront costs make them particularly suitable for small-scale or pilot projects, though with the tradeoff of reduced long-term efficiency and profitability. Financial modeling under standardized assumptions (including \$30/ton feedstock costs and \$0.10/kWh electricity prices) reveals that while CSTR systems achieve faster 4-7-year capital recovery, TPAD systems deliver superior 15-20% returns on investment over a 10-year operational lifespan.

Table 7: Comparative Analysis of AD Systems

Parameter	TPAD	CSTR
Capital Cost	\$1,200-1,800/ton VS	\$800-1,200/ton VS
Methane Yield	65-85%	50-70%
Operational Cost	\$50,000-70,000/yr	\$30,000-50,000/yr
Payback Period	5-8 years	4-7 years

Assumptions: Feedstock = \$30/ton, electricity = \$0.10/kWh, 10-year lifespan, 5% discount rate.

Policy frameworks play a pivotal role in shaping AD adoption trajectories. The European Union's Renewable Energy Directive II (RED II) establishes robust incentives, including €0.08-0.15/kWh feed-in tariffs and biomethane injection bonuses, creating stable market conditions for AD development. Developing nations employ alternative mechanisms such as India's SATAT program and international carbon credit systems, though these often face implementation challenges, including inconsistent funding and regulatory fragmentation. Significant barriers persist across all regions. Capital requirements remain prohibitive in many developing contexts, where TPAD costs may exceed 150% of annual rural incomes. Technical capacity limitations, including shortages of trained maintenance personnel, further constrain system reliability and performance. These challenges are compounded by policy inconsistencies, particularly in African and Southeast Asian markets where support mechanisms lack stability or sufficient scale.

To address these barriers, integrated financing models combining public investment, private partnerships, and carbon credit mechanisms show particular promise. Such approaches can help bridge the gap between high initial costs and long-term returns, while policy harmonization efforts could improve market stability. Future development strategies should prioritize both technological optimization and enabling policy frameworks to fully realize AD's potential in global renewable energy portfolios. This analysis underscores that while anaerobic digestion presents a technically viable pathway for renewable energy production and waste management,

its economic scalability depends critically on context-appropriate system selection, targeted policy support, and innovative financing mechanisms tailored to regional circumstances.

4.1 Challenges of Geographic and Economic Scalability

The global adoption of anaerobic digestion (AD) systems exhibits significant regional variations due to disparities in financial resources, infrastructure development, and policy frameworks (Vasco-Correa et al., 2018) [81]. This section examines these challenges through a comparative analysis of developed and developing regions, supported by empirical data (Table 8). In developed regions such as the EU and North America, AD systems benefit from established infrastructure for grid injection, supported by robust policy mechanisms like the EU's Renewable Energy Directive II (RED II 2018/2001). These regions have implemented advanced technological solutions, including AI-driven process optimization and membrane-based biogas upgrading systems, which significantly enhance operational efficiency. However, challenges persist, particularly regarding market stability. An over-reliance on feed-in tariffs creates vulnerability to policy shifts, while high operational costs for labor and maintenance continue to pressure profitability margins (UNEP, 2023). Developing regions present a markedly different scenario. Countries in Sub-Saharan Africa and Southeast Asia possess abundant feedstock resources, particularly agricultural byproducts and municipal waste, which offer cost-effective inputs for AD systems (Huang, 2024). Small-scale residential digesters have shown particular promise in rural applications, with initiatives like India's SATAT program demonstrating successful off-grid implementation (UNEP, 2023).

However, these regions face substantial barriers to adoption. The initial capital costs often exceed 150% of average annual rural incomes, creating significant financial hurdles (Huang, 2024). In Sub-Saharan Africa, for instance, decentralized fixed-dome systems like those implemented in Kenya have reduced household energy costs by 40%, yet face extended capital recovery periods of 12-15 years due to limited subsidy support (Kulkarni et al., 2021). Additional challenges include a chronic shortage of local technical expertise and inadequate maintenance infrastructure (UNEP, 2023). Table 8 provides a comparative overview of key scalability factors across regions. The data reveals stark contrasts in capital expenditure recovery timelines, ranging from 5-7 years in the EU and North America to 12-15 years in Sub-Saharan Africa. Policy support follows a similar gradient, from strong legislative frameworks in developed regions to weak or emerging structures in developing economies. Interestingly, social acceptance presents an inverse relationship, with rural areas in developing regions showing higher receptivity than urban centers in Southeast Asia. The economic viability of AD systems is further illustrated through technology-specific analysis (Figure 3). Two-phase anaerobic digestion (TPAD) systems, while requiring 20-50% higher capital investment (\$1,200-1,800 per ton volatile solids) compared to conventional single-tank reactors, demonstrate superior long-term performance with 29% greater methane production (Yu et al., 2020). Model this cost-benefit relationship (Figure 3) for a representative 10,000-ton/year facility, showing how TPAD's enhanced yield offsets its higher initial costs over time.

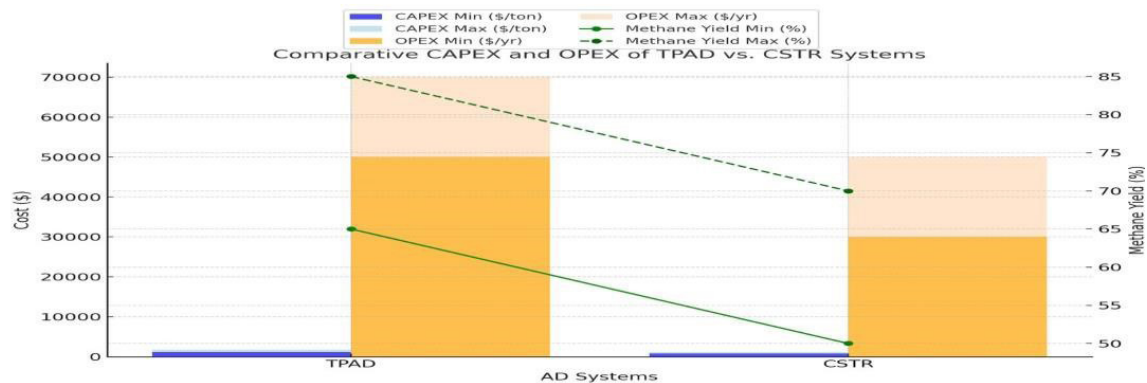


Figure 3: Cost-Benefit Analysis of TPAD vs. CSTR Systems for a 10,000-ton/year Biogas Plant.

Comparison of long-term methane yield and economic viability between Two-Phase Anaerobic Digestion (TPAD) and Continuous Stirred Tank Reactor (CSTR) systems, demonstrating TPAD's higher initial capital costs offset by 29% greater methane production over a 10-year operational lifespan (Yu et al., 2020).

These findings underscore two critical observations. First, legislative frameworks and financial incentives remain fundamental drivers of successful AD deployment across all regions (Khalid et al., 2020) [83]. Second, the pathway to broader adoption requires tailored solutions that address region-specific combinations of technical, financial, and policy challenges (Ibarra-Esparza et al., 2023) [84]. For developed economies, this means optimizing existing infrastructure and policy mechanisms, while developing regions require targeted investments in capacity building and financial support structures to overcome their unique adoption barriers.

Table [8] Comparative scalability factors by region.

Factor	EU/North America	Sub-Saharan Africa	Southeast Asia
Avg. CAPEX Recovery	5–7 years	12–15 years	8–10 years
Policy Support	Strong (RED II)	Weak	Emerging
Social Acceptance	Moderate	High (rural)	Low (urban)

5. CASE EXAMPLES AND ECONOMIC FEASIBILITY OF ANAEROBIC DIGESTION SYSTEMS

Case examples showcase the successful deployment of anaerobic digestion (AD) systems across diverse economic landscapes. In emerging economies, small-scale farming ventures have embraced closed-loop biodigesters, including fixed dome and floating drum designs, to fulfill local energy demands. These systems, frequently built from locally available materials, deliver affordable energy solutions while transforming agricultural waste into nutrient-dense fertilizers (Kulkarni et al., 2021) [85]. For instance, a research study conducted in rural India revealed that biogas generation from small-scale digesters cut household energy costs by 40% and enhanced sanitation through improved waste management practices. On a larger scale, collective anaerobic digestion systems on dairy farms exemplify the potential for economies of scale. Shared facilities process organic waste from numerous farms, boosting methane recovery

and electricity production. A case study from the United States indicated that dairy farms with herds exceeding 500 cows realized considerable cost savings through methane capture and energy generation, aided by subsidies and energy buyback agreements (Sharara et al., 2020) [86]. In urban settings, the handling of municipal solid waste has greatly benefited from large-scale AD facilities. For example, a plant in Sweden treats 200,000 tons of organic waste each year to produce biomethane, which serves as fuel for vehicles. This operation generates income through energy sales and carbon credits, highlighting the financial viability of AD systems when backed by supportive regulations and market incentives. National initiatives like India's SATAT program have further propelled the adoption of decentralized AD systems. By offering financial incentives and technical training, the program has empowered rural communities to implement biogas technology on a larger scale. Pilot studies in targeted areas have documented a 20–30% rise in adoption rates, demonstrating the effectiveness of policy-driven interventions. Furthermore, large-scale AD facilities for municipal solid waste provide considerable opportunities for renewable energy generation and waste management. Facilities with capacities exceeding 75,000 tons annually have shown economic viability, especially in countries like Sweden and Germany, where renewable energy tariffs and waste management fees enhance financial sustainability (Smith et al., 2021) [87]. The use of biogas as vehicle fuel presents greater revenue possibilities compared to electricity or natural gas sales, further improving the economic attractiveness (Dolan et al., 2011) [88]. Nevertheless, global uptake varies due to obstacles such as substantial capital expenses, material handling challenges, and digestate management (Gadaleta et al., 2021) [89]. Ongoing research concentrates on optimizing pre-treatment and post-treatment processes to boost biogas yields while reducing carbon emissions and energy usage (Fan et al., 2018), [90].

6. CONCLUSION

Anaerobic digestion (AD) has established itself as a pivotal technology for sustainable biogas production, effectively addressing the dual challenges of waste management and renewable energy generation. This comprehensive review has systematically examined the biochemical foundations of AD, emphasizing the critical role of microbial consortia and the optimization of key operational parameters such as temperature, pH, and hydraulic retention time. A central finding is the importance of feedstock pretreatment, particularly for lignocellulosic materials, in enhancing biodegradability and maximizing biogas yields. Recent technological advancements have significantly improved AD efficiency and applicability. Notable innovations include the development of Two-Phase Anaerobic Digestion (TPAD) systems, which spatially separate hydrolysis and methanogenesis to optimize each process stage. Advances in preprocessing techniques—including thermal, chemical, and enzymatic treatments—have demonstrated marked improvements in the digestibility of complex substrates. Furthermore, the integration of AI-driven monitoring systems has enabled real-time process adjustments, reduced inefficiencies and enhancing overall system performance.

Despite these advancements, several critical challenges hinder the widespread adoption of AD. Economic barriers, including high capital and operational expenditures, remain a persistent obstacle. The energy-intensive nature of biogas purification processes further complicates the economic viability of producing commercial-grade biomethane. Additional challenges include the inherent variability of feedstock quality and availability, which threatens

process stability, and the lack of consistent regulatory frameworks across regions, which undermines scalability. To address these limitations, future efforts must prioritize three key areas:

1. **Technological innovation**, particularly the refinement of AI applications for predictive process control and the development of hybrid systems integrating AD with complementary renewable technologies (e.g., solar, wind) to enhance resilience;
2. **Policy development**, with an emphasis on creating standardized incentives such as subsidies and carbon credits to encourage investment; and
3. **Digestate valorization**, exploring novel applications in agriculture, material science, and even specialized fields like dental biomaterials to improve the circular economy potential of AD systems.

For these advancements to translate into tangible progress, coordinated action is required. Policymakers must implement targeted incentives to accelerate adoption, while researchers should focus on optimizing digestate utilization and advancing AI integration for smarter process management. Such multidisciplinary efforts will be essential to overcoming current limitations and unlocking the full potential of AD. In summary, anaerobic digestion represents more than a renewable energy solution—it is a platform for innovation at the intersection of waste management, energy production, and material science. By addressing the technical, economic, and policy challenges identified in this review, AD can play an expanded role in global sustainability efforts while fostering novel applications across diverse sectors, including healthcare and biotechnology.

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