Anaerobic Digestion: A Survey of Microbial Community Structure and Biogas Production

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Abstract

This survey comprehensively examines anaerobic digestion (AD), emphasizing the critical role of microbial community structures in biogas production. It elucidates core concepts, stages, and terminologies associated with AD, highlighting its significance in waste management and renewable energy. The survey explores the diversity and interactions within microbial communities, detailing how these influence digestion efficiency and biogas yield. It discusses substrate specificity and physicochemical properties, emphasizing their impact on digestion performance and strategies for optimization. The role of inoculum in initiating and sustaining digestion is analyzed, alongside substrate specificity's effect on microbial activity. Pretreatment methods are reviewed for their potential to enhance substrate biodegradability, thus improving biogas production. The survey also addresses the influence of pH, temperature, nutrient availability, and substrate concentration on digestion performance. Technological advancements, including microbial electrochemical technologies and machine learning approaches, are highlighted for their contributions to optimizing biogas production. The survey concludes with a discussion on current challenges and future research directions, underscoring the need for advanced modeling techniques and innovative pretreatment strategies to enhance AD efficiency and sustainability. Overall, this survey provides a critical overview of anaerobic digestion, offering insights into maximizing biogas production and advancing sustainable energy solutions.

1 Introduction

1.1 Structure of the Survey

This survey meticulously examines anaerobic digestion, focusing on microbial community structures and their impact on biogas production. It begins with an overview of anaerobic digestion's fundamental concepts, underscoring its importance in waste management and renewable energy. A detailed background section elucidates the core concepts, stages, and key terminologies associated with the process. Subsequent sections explore microbial community diversity, roles, and interactions, highlighting their influence on digestion efficiency and biogas yield. The survey also discusses inoculum and substrate specificity, analyzing various substrates and their effects on digestion. Additionally, it provides a thorough analysis of physicochemical properties affecting digestion performance and strategies for optimization. The section on biogas production and applications reviews factors influencing biogas quality and quantity, while showcasing technological advancements in renewable energy. The survey concludes with a critical overview of current challenges and future research directions, charting the field's trajectory [1].The following sections are organized as shown in Figure 1.

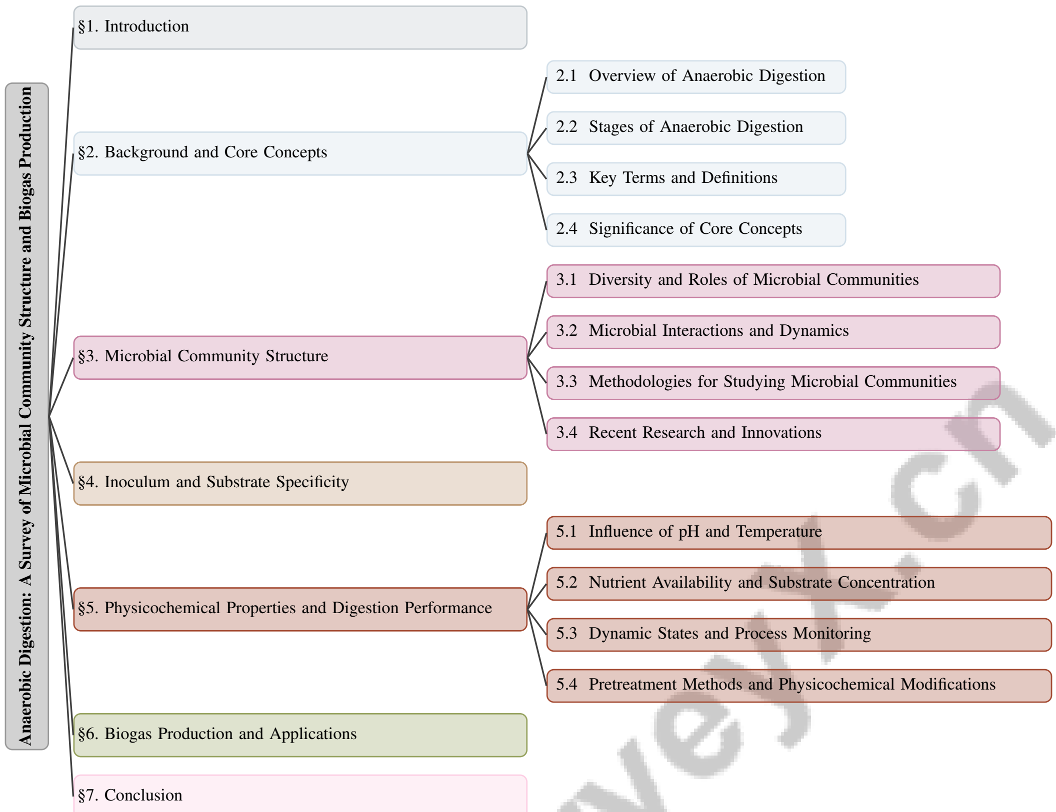

Figure 1: chapter structure

2 Background and Core Concepts

2.1 Overview of Anaerobic Digestion

Anaerobic digestion (AD) is a vital biological process transforming organic waste into biogas and digestate through microbial activity in oxygen-free environments, playing a key role in renewable energy production and sustainable waste management [2]. It offers an alternative to fossil fuels by converting biomass into biogas for various energy applications. The process involves stages like feedstock preparation, digestion, biogas upgrading, and utilization, aligning with sustainability goals and efficient waste management [1]. However, volatile fatty acids (VFAs) accumulation, especially propionate, can destabilize AD, requiring effective management to enhance methanogenic efficiency [3].

In wastewater treatment, AD enables energy generation and by-product recovery, treating wastewater as a resource [4]. Anaerobic co-digestion (ACoD) of food waste, wheat straw, and cattle manure has proven effective, with microalgae integration further enhancing biogas yields [5, 6]. Current models often assume homogeneity, which is inaccurate for real-world conditions, particularly in plug-flow reactors, highlighting the need for improved models and predictive tools for optimizing AD performance in low-carbon energy contexts [7].

AD is integral to renewable energy initiatives, effectively managing organic waste while generating biogas. Despite its benefits, challenges like conversion efficiency, process stability, and economic viability remain, necessitating ongoing research and innovation [8, 9, 10, 11, 12].

2.2 Stages of Anaerobic Digestion

Anaerobic digestion involves four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each crucial for biogas production [13]. Hydrolysis breaks down complex polymers into soluble monomers, often the rate-limiting step, especially with lignocellulosic biomass [13]. Acidogenesis converts these monomers into VFAs, alcohols, hydrogen, and carbon dioxide, with microbial diversity influencing efficiency and stability [13]. Acetogenesis transforms VFAs into acetic acid, carbon dioxide, and hydrogen, feeding methanogenesis [13]. Methanogenesis, producing methane and carbon dioxide, is sensitive to conditions like pH and temperature, with methanogenic archaea requiring specific environments for optimal performance [14]. Models like ADM1 simulate these stages but face challenges due to assumptions of homogeneity, affecting biochemical reaction efficiency [15].

2.3 Key Terms and Definitions

Understanding anaerobic digestion requires familiarity with key terms. Anaerobic co-digestion (ACoD) involves digesting multiple waste types, enhancing biogas production through improved substrate use and nutrient balance [5]. "Inoculum" refers to the microbial consortium initiating and sustaining organic matter breakdown, crucial for process stability and efficiency [4, 16]. "Microbial community structure" encompasses the diversity and distribution of microorganisms, affecting metabolic pathways and interactions essential for organic matter breakdown [8, 13]. "Substrate specificity" denotes microbial preference for certain organic matter types, influencing degradation rate and biogas production efficiency [17, 18, 19]. Physicochemical properties like pH, temperature, and nutrient availability are critical for maximizing biogas production and process resilience [8, 13, 17, 18]. Mathematical modeling terms, such as Liouvillian solutions and Abel's equations, are relevant for developing models that optimize the digestion process [20].

2.4 Significance of Core Concepts

Core concepts in anaerobic digestion are essential for optimizing biogas production, environmental sustainability, and energy efficiency. The microbial community structure is pivotal, governing metabolic pathways and influencing biogas yield and quality [2]. Optimizing interspecies electron transfer is crucial, as traditional methods limit methane production and system performance, necessitating microbial diversity and stability through interactions like cross-feeding networks [8].

Substrate specificity affects degradation rate and efficiency. Utilizing diverse feedstocks can mitigate challenges like variability and low efficiency, optimizing biogas yield [8]. Physicochemical properties, such as temperature and pH, must be regulated to optimize microbial activity and prevent disruptions, balancing economic, technical, and environmental considerations [13].

Advanced modeling techniques, including convection-diffusion-reaction equations, improve predictive accuracy by accounting for complex microbial-environment interactions, addressing limitations of models like ADM1 [21]. Dynamic strategies, similar to extremum seeking techniques, allow real-time operational adjustments, enhancing performance [22].

As the bio-based economy grows, these core concepts are crucial for sustainable energy solutions. Maintaining low volatile fatty acid concentrations, such as propionate, ensures process stability, while valorizing waste from biodigester plants addresses Water-Energy-Waste Nexus challenges, offering integrated solutions for energy and water management [3]. These concepts provide a framework for optimizing anaerobic digestion, maximizing biogas production, and ensuring economic viability, advancing renewable energy strategies [7].

In recent studies of anaerobic digestion, understanding the dynamics of microbial communities has become increasingly crucial. The complexity of these communities is underscored by their hierarchical structure, which influences both their diversity and the syntrophic relationships that develop among different microbial species. This is particularly important as these interactions play a significant role in optimizing biogas production and enhancing sustainability within the process. Figure 2 illustrates this hierarchical structure, highlighting key concepts such as diversity and methodologies for studying microbial communities. The figure categorizes the main ideas into primary categories, subcategories, and detailed insights, effectively emphasizing the interconnections and contributions of these microbial communities to the overall efficiency of anaerobic digestion systems. By examining these relationships and the innovations in research methodologies, we can better understand how to leverage microbial dynamics for improved biogas yields.

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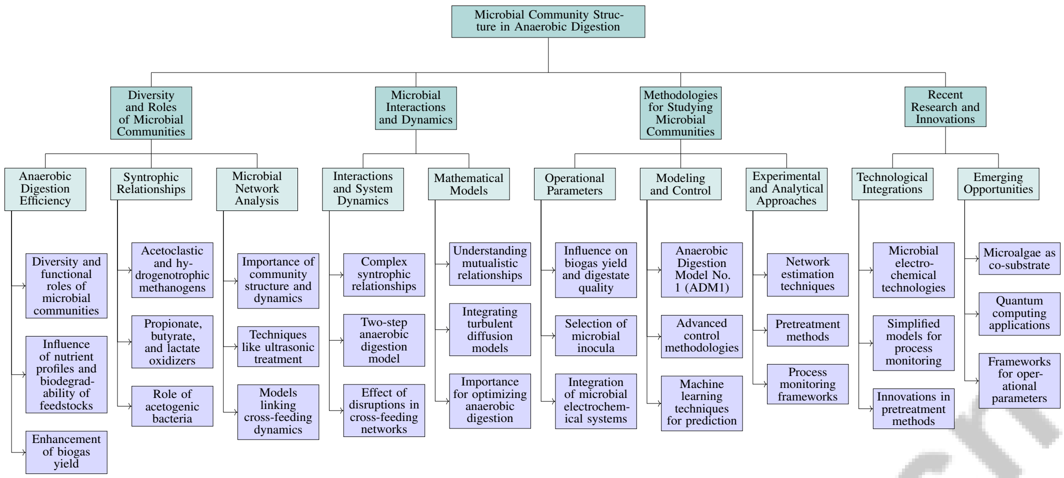

Figure 2: This figure illustrates the hierarchical structure of microbial community dynamics in anaerobic digestion, highlighting key concepts such as diversity, syntrophic relationships, methodologies for studying microbial communities, and recent innovations. It categorizes the main ideas into primary categories, subcategories, and detailed insights, emphasizing the interconnections and contributions to biogas production and sustainability.

3 Microbial Community Structure

3.1 Diversity and Roles of Microbial Communities

Anaerobic digestion efficiency and stability are intricately linked to the diversity and functional roles of microbial communities, comprising bacteria and archaea essential for decomposing complex organic substrates into simpler compounds, thus facilitating biogas production [13]. The diversity within these communities is influenced by the nutrient profiles and biodegradability of feedstocks, such as agricultural waste, food industry by-products, and municipal waste, which together create a nutrient-rich environment that supports diverse microbial populations and enhances biogas yield [2].

Syntrophic relationships among microbial groups, including acetoclastic and hydrogenotrophic methanogens and propionate, butyrate, and lactate oxidizers, are vital for converting organic matter into methane [3]. Acetogenic bacteria play a pivotal role by breaking down volatile fatty acids into acetic acid, hydrogen, and carbon dioxide, which methanogenic archaea subsequently convert into methane and carbon dioxide [21].

Recent advancements in microbial network analysis highlight the importance of understanding community structure and dynamics. Techniques such as ultrasonic treatment during pretreatment and anaerobic digestion have shown promise in enhancing biogas yields by optimizing microbial interactions. Models linking cross-feeding dynamics to community diversity reveal that microbial interaction structures can lead to diversity tipping points, significantly impacting digestion performance [23]. Adaptive control strategies are necessary to manage the dynamic nature of microbial communities, ensuring process stability and efficiency [7].

As illustrated in Figure 3, this figure highlights the key aspects of microbial communities in anaerobic digestion, emphasizing microbial diversity, syntrophic relationships, and advancements in process optimization. Leveraging microbial community roles and optimizing interactions can enhance anaerobic digestion processes, aligning with renewable energy and waste management objectives [14].

3.2 Microbial Interactions and Dynamics

Microbial interactions and dynamics are central to the efficiency and stability of anaerobic digestion. These interactions involve complex syntrophic relationships where microbial groups depend on each other for substrates and metabolic by-products, aiding in the breakdown of complex organic materials

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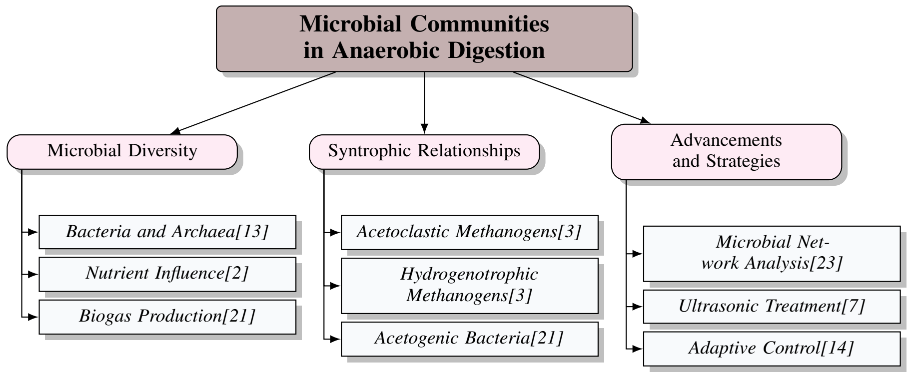


Figure 3: This figure illustrates the key aspects of microbial communities in anaerobic digestion, highlighting microbial diversity, syntrophic relationships, and advancements in process optimization.

[18]. The two-step anaerobic digestion model, utilizing interconnected chemostats, illustrates how microbial interactions influence system dynamics and digestion performance [24].

Syntrophic interactions, particularly between acetogenic bacteria and methanogenic archaea, are critical for converting volatile fatty acids into methane. Disruptions in cross-feeding networks can cause shifts in microbial diversity, affecting digestion efficiency [25]. Ammonia selectively inhibits methanogenic populations, especially acetoclastic methanogens, highlighting the need for a balanced microbial ecosystem [10].

Mathematical models are instrumental in understanding these interactions, providing insights into mutualistic relationships within microbial communities. Models exploring syntrophic dynamics offer a broader perspective compared to traditional growth-focused models [26]. Integrating turbulent diffusion models, such as CHAD-TD, improves anaerobic digestion simulations by accurately capturing mixing dynamics that influence microbial interactions [15]. Understanding microbial dynamics is crucial for optimizing anaerobic digestion, especially in renewable energy and waste management [23].

3.3 Methodologies for Studying Microbial Communities

Studying microbial communities in anaerobic digestion systems is essential for improving biogas production and stability. Operational parameters like pH, temperature, organic loading rate, and hydraulic retention time are influenced by microbial community dynamics, affecting biogas yield and digestate quality. Selecting appropriate microbial inocula and integrating technologies like microbial electrochemical systems are crucial for optimizing interactions and enhancing methane production, especially in the presence of inhibitors like propionate [8, 3, 18].

Mathematical models, including the Anaerobic Digestion Model No. 1 (ADM1), simulate complex biochemical processes in digesters, providing a framework for evaluating system stability and behavior [4]. Simplified models, such as the SADM, enhance understanding by describing the growth dynamics of acidogenic and methanogenic microorganisms [21].

Advanced control methodologies, including rapid feedback mechanisms, dynamically adjust operational parameters, optimizing biogas production in response to real-time changes [27]. Machine learning techniques predict adverse events based on operating conditions, enhancing predictive capabilities [7].

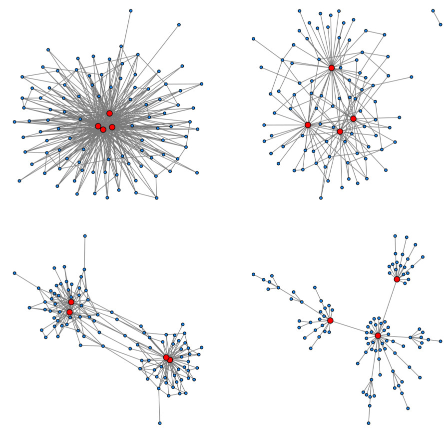
Network estimation techniques, like the hw.glasso method, improve understanding of microbial interactions by incorporating structural information about network hubs [28]. The CHAD-TD method provides a robust framework for simulating anaerobic digestion processes, accurately representing mass transfer dynamics and biochemical transformations [15].

Experimental approaches, such as semi-continuous anaerobic digestion with varying organic loading rates, offer insights into community dynamics under different conditions [5]. Pretreatment methods, including potassium hydroxide (KOH) and ultrasonic applications, enhance biogas production by modifying substrate properties [29].

Methodologies like the Unscented Kalman Filter (UKF) offer comprehensive frameworks for process monitoring, providing insights into real-world applications [30]. Bayesian uncertainty quantification methods, such as VarBUQ, offer robust frameworks for understanding and applying uncertainty quantification in anaerobic digestion models [31].

$$\alpha = \frac{D}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};\ u_f = \frac{S_{\mathrm{ch,in}}}{K_{S,\mathrm{ch}}};\ u_g = \frac{S_{\mathrm{ph,in}}}{K_{S,\mathrm{ph}}};\ u_h = \frac{S_{\mathrm{H_2,in}}}{K_{S,\mathrm{H_2}}};$$
$$\omega_0 = \frac{K_{S,\mathrm{ch}}}{K_{S,\mathrm{ph}}} \frac{224}{208} (1 - Y_{\mathrm{ch}});\ \omega_1 = \frac{K_{S,\mathrm{ph}}}{K_{S,\mathrm{H_2}}} \frac{32}{224} (1 - Y_{\mathrm{ph}});$$
$$\omega_2 = \frac{16}{208} \frac{K_{S,\mathrm{ch}}}{K_{S,\mathrm{H_2}}};$$
$$\phi_1 = \frac{k_{m,\mathrm{ph}} Y_{\mathrm{ph}}}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};\ \phi_2 = \frac{k_{m,\mathrm{H_2}} Y_{\mathrm{H_2}}}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};$$
$$K_P = \frac{K_{S,\mathrm{H_2},c}}{K_{S,\mathrm{H_2}}};\ K_I = \frac{K_{S,\mathrm{H_2}}}{K_{I,\mathrm{H_2}}};$$
$$k_A = \frac{k_{\mathrm{dec,ch}}}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};\ k_B = \frac{k_{\mathrm{dec,ph}}}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};\ k_C = \frac{k_{\mathrm{dec,H_2}}}{k_{m,\mathrm{ch}} Y_{\mathrm{ch}}};$$
$$\mu_0(s_0, s_2) = \frac{s_0}{1+s_0} \frac{s_2}{K_P + s_2};\ \mu_1(s_1, s_2) = \frac{\phi_1 s_1}{1+s_1} \frac{1}{1+K_I s_2};$$
$$\mu_2(s_2) = \frac{\phi_2 s_2}{1+s_2}.$$

(a) The image contains a mathematical equation related to chemical kinetics and thermodynamics.[4]



(b) Network Dynamics: Exploring the Spread of Information and Influence[28]

Figure 4: Examples of Methodologies for Studying Microbial Communities

As illustrated in Figure 4, studying microbial communities involves diverse methodologies. One approach uses mathematical equations related to chemical kinetics and thermodynamics to model reaction rates crucial to microbial processes, providing insights into biochemical pathways. Another focuses on network dynamics, exploring information and influence spread within microbial communities, visualizing interaction flows and connection complexities. These methodologies are integral to understanding microbial ecosystem functions and influences within broader ecological contexts [4, 28].

3.4 Recent Research and Innovations

Recent research in anaerobic digestion has advanced understanding of microbial community dynamics and optimized biogas production processes. Integrating microbial electrochemical technologies (MET) with anaerobic digestion (AD) has shown potential for enhancing methane production and mitigating propionate accumulation, requiring further validation of energy benefits [3].

As illustrated in Figure 5, recent innovations in anaerobic digestion are categorized into microbial technologies, pretreatment methods, and quantum computing applications, highlighting their contributions to process optimization and biogas production efficiency. Simplified models, such as those analyzed by Meadows et al., capture essential biogas production dynamics, offering practical applications for effective process monitoring and optimization, despite not replicating all behaviors of complex models like ADM1 [21].

Innovations in pretreatment methods, emphasized by Uddin et al., focus on developing efficient techniques and optimizing process conditions to improve the economic viability of anaerobic digestion technologies. Investigations into primary treatment in High Rate Algal Ponds (HRAPs) further highlight its impact on AD efficiency [32].

Integrating microalgae as a co-substrate in anaerobic co-digestion with sewage sludge presents promising opportunities for enhancing biogas yields, necessitating comprehensive lab-scale and pilot-scale experiments to understand involved dynamics fully [6].

Quantum computing applications for optimizing complex problems, such as biomass optimization, show significant performance improvements, suggesting potential enhancements for anaerobic digestion processes [33]. The framework introduced by Sarker et al. categorizes research into operational parameters affecting anaerobic digestion, highlighting interdependencies and their collective impact on biogas production efficiency [8].

These innovations and findings deepen understanding of microbial communities in anaerobic digestion systems, facilitating process optimization and advancing sustainable energy production goals [11].

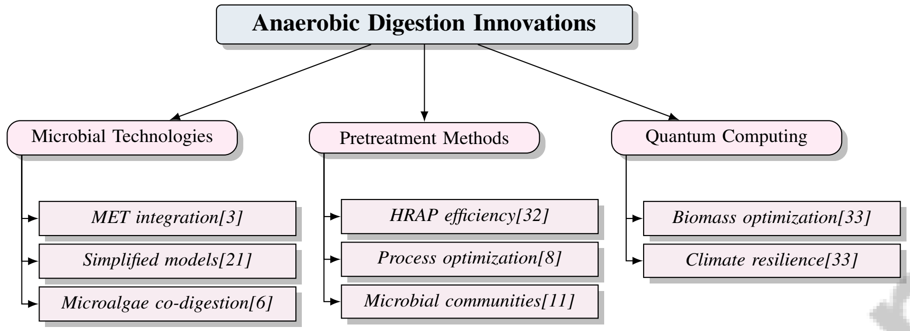


Figure 5: This figure illustrates recent innovations in anaerobic digestion, categorized into microbial technologies, pretreatment methods, and quantum computing applications, highlighting their contributions to process optimization and biogas production efficiency.

4 Inoculum and Substrate Specificity

4.1 Role of Inoculum in Anaerobic Digestion

The inoculum is pivotal in anaerobic digestion, providing the microorganisms necessary for converting organic matter into biogas. Its selection and acclimatization are crucial to optimize digestion performance, as the microbial community composition significantly influences the metabolic pathways involved [5]. Utilizing acclimatized microorganisms from established biogas plants enhances methane production and system stability [5]. Mutualistic interactions within the microbial community are essential for stable digestion, with syntrophic bacterial species coexisting to efficiently convert substrates [26]. Co-digestion strategies further enhance nutrient mobilization and reduce treatment costs [6].

The resilience of inoculum to inhibitors like ammonia is vital, as such compounds can disrupt methanogenesis and destabilize the process. Research into acclimatization and mitigation strategies has focused on enhancing stability in ammonia-rich environments, especially with lignocellulosic biomass, where pretreatment costs are significant [10, 19]. Strategic inoculum management is key to optimizing anaerobic digestion, ensuring efficient biogas production while addressing challenges related to substrate variability and process inhibition [8].

4.2 Substrate Specificity and Microbial Activity

Substrate specificity is a critical factor in anaerobic digestion efficiency, impacting microbial activity and overall performance. Optimal substrate selection and mixing ratios, such as a 75:25 food waste to cattle manure ratio, can maximize biogas yield [5]. Diverse feedstocks offer opportunities to enrich the nutrient profile and support various microbial communities, but their physicochemical properties and biodegradability must be managed to prevent process inhibition and ensure stable operation [17].

Experimental acclimation cycles and degradation tests assess microbial adaptation to substrate changes, essential for efficient digestion [3]. However, technological challenges, such as the high costs of electrode materials and sluggish oxygen reduction reactions in microbial fuel cells, impede the integration of advanced technologies in biogas plants [34]. Substrate specificity determines optimal conditions for biogas production, with factors like feedstock composition, organic loading rates, and nutrient balance impacting microbial dynamics and decomposition efficiency, ultimately affecting biogas and digestate yield and quality [8, 13, 18, 5]. By optimizing substrate selection and addressing technological challenges, anaerobic digestion performance can be enhanced, promoting sustainability in waste management practices.

Method Name	Pretreatment Techniques	Optimization Parameters	Efficiency Enhancement
MP[19]	Physical, Chemical, Biological	Oxygen Supply Levels	Improve Methane Yield
MMDAD[35]	Thermal, Chemical	Reactor Length	Improving Biogas Yield
OIA[36]	-	Hydraulic Retention Time	Improving Biogas Yield

Table 1: Table summarizing various pretreatment methods and their impact on anaerobic digestion efficiency, highlighting the specific techniques employed, optimization parameters considered, and the resultant efficiency enhancements. The methods include physical, chemical, biological, and thermal pretreatments, each aiming to improve methane or biogas yield.

4.3 Pretreatment Methods and Their Impact

Pretreatment methods are crucial for enhancing anaerobic digestion efficiency by increasing substrate biodegradability and microbial access to organic matter. Various technologies—physical, chemical, and biological—are evaluated on a pilot scale to optimize biogas production [19]. These strategies are assessed based on their ability to solubilize complex organics, thus enhancing digestion. Table 1 provides a comprehensive overview of different pretreatment methods, their optimization parameters, and their effectiveness in enhancing the efficiency of anaerobic digestion processes.

Mechanical pretreatments, such as milling and grinding, reduce particle size and increase surface area, aiding the breakdown of lignocellulosic biomass resistant to microbial degradation. Microwave and thermal methods use heat to disrupt substrate structures, promoting the release of intracellular compounds for microbial metabolism [37]. Chemical pretreatments utilize acids, alkalis, or oxidizing agents to solubilize organic matter, while biological methods employ specific enzymes or microbial consortia for pre-digestion, enhancing subsequent breakdown during anaerobic digestion.

Numerical simulations evaluate pretreatment impacts by considering parameters like reactor length, inlet velocity, hydraulic retention time (HRT), and diffusion coefficient, providing insights for optimizing pretreatment processes in anaerobic systems [35]. However, challenges in assessing observability and identifiability in these models complicate their real-time application [36]. Selecting appropriate pretreatment methods is critical for maximizing anaerobic digestion efficiency. By enhancing substrate availability through diverse feedstocks—such as grass, which requires low water and thrives on non-arable land—and optimizing parameters like pH, temperature, organic loading rate, and HRT, pretreatment strategies can significantly boost biogas yield and promote sustainable organic waste management. Methods including mechanical, thermal, chemical, and biological pretreatments disrupt complex lignocellulosic structures, improving energy balance and efficiency in anaerobic digestion processes [8, 37].

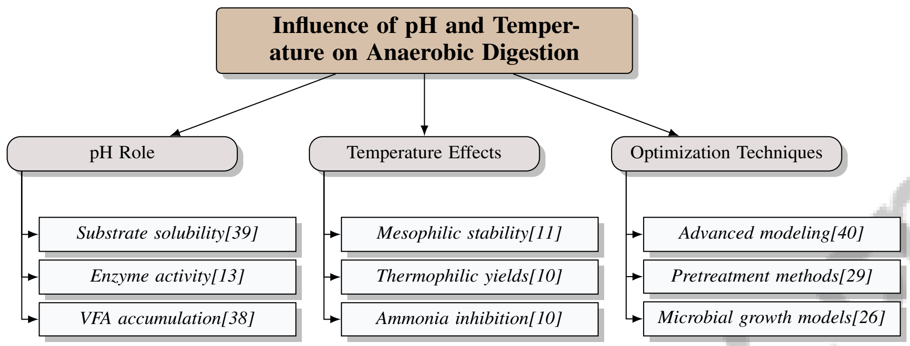
5 Physicochemical Properties and Digestion Performance

Understanding physicochemical properties is crucial for optimizing anaerobic digestion processes. Key factors such as pH and temperature significantly influence microbial activity and biogas production, impacting microbial metabolic pathways and overall process stability.

5.1 Influence of pH and Temperature

pH and temperature are pivotal in anaerobic digestion, directly affecting microbial metabolic activities, thereby influencing efficiency and stability [13, 38]. Optimal conditions are essential for maximizing microbial growth rates and digestion robustness [5]. The pH level affects substrate solubility and enzyme activity; deviations can lead to volatile fatty acid (VFA) accumulation, causing instability and reduced methane production [39]. Advanced modeling techniques are needed to predict and optimize these dynamics, as traditional models like ADM1 may not capture VFA interactions' complexity [40]. Temperature also influences microbial metabolism, with mesophilic (around 37°C) and thermophilic (approximately 55°C) conditions offering distinct advantages. Mesophilic digestion is stable, while thermophilic conditions enhance substrate breakdown and biogas yields, though they may increase ammonia levels, inhibiting microbial activity [11, 10]. Integrating pretreatment methods, such as ultrasonic application, can optimize pH and temperature effects by disrupting lignocellulosic structures, enhancing substrate availability [29].

Figure 6 illustrates the influence of pH and temperature on anaerobic digestion, highlighting the roles of substrate solubility, enzyme activity, and VFA accumulation in pH regulation, while detailing the effects of mesophilic and thermophilic conditions on digestion stability and yields. It also outlines optimization techniques including advanced modeling, pretreatment methods, and microbial growth models. Models incorporating substrate and intermediate product influences on microbial growth rates provide insights into anaerobic digestion dynamics [26].



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5.2 Nutrient Availability and Substrate Concentration

Nutrient availability and substrate concentration are critical for anaerobic digestion performance. A balanced supply of macro and micronutrients sustains microbial activities necessary for organic matter breakdown into biogas [13, 5]. Substrate concentration affects biogas production rates; high concentrations can boost microbial growth and yields but may also cause instability due to VFA accumulation, lowering pH and inhibiting methanogenic activity [39, 38]. Maintaining optimal substrate levels is crucial for balancing organic matter breakdown and microbial processing capacity. Dynamic optimization models offer insights into nutrient availability, substrate concentration, and microbial activity interactions, enabling simulations to identify optimal conditions for maximizing biogas production while minimizing inhibition risks [40]. Co-digestion strategies, processing multiple substrates simultaneously, can enhance nutrient availability and digestion efficiency [6, 34].

5.3 Dynamic States and Process Monitoring

Benchmark	Size	Domain	Task Format	Metric
UKF-ADM1[30]	1,000	Anaerobic Digestion	State Estimation	NRMSE
VarBUQ[31]	1,764	Biochemical Reaction Networks	Parameter Estimation	p-value
HRAP-BM[32]	260	Wastewater Treatment	Performance Evaluation	NH4+-N removal, COD removal
HRAP-LCA[41]	1,950	Environmental Science	Life Cycle Assessment	Climate Change, Ozone Depletion
AD-MET[3]	791,990	Microbial Electrochemistry	Propionate Degradation Tests	Methane yield, COD removal
TMFC[14]	12	Microbial Fuel Cells	Power Production Assessment	Power Density, Current Density

Table 2: This table presents a comprehensive overview of various benchmarks utilized in the field of anaerobic digestion and related domains. It details the size, domain, task format, and the metrics employed for each benchmark, providing insight into their applications and evaluation criteria.

Monitoring dynamic states and process parameters is essential for optimizing biogas production and ensuring process stability. Continuous assessment of variables such as substrate concentration, pH, temperature, and biogas yield is crucial for maintaining optimal microbial activity and preventing inhibition. Advanced techniques, including bifurcation theory, analyze stability and equilibria in anaerobic digestion systems under varying conditions [38]. Mathematical models, particularly those

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based on ADM1, simulate digesters' dynamic behavior. Simplifying ADM1 through algebraic and geometric approaches enhances model observability and identifiability, allowing accurate monitoring and control of critical system states [36]. These models facilitate understanding complex interactions within the digestion process, aiding in developing strategies to enhance biogas production and system resilience. Algorithmic advancements, like the constrained Unscented Kalman Filter (cUKF-add), improve state estimation accuracy, enabling real-time operational parameter adjustments to optimize performance [30]. Integrating advanced monitoring techniques with predictive modeling enhances disturbance detection and response, ensuring efficient and sustainable anaerobic digestion system operation. Table 2 offers a detailed examination of representative benchmarks that are crucial for understanding and optimizing dynamic states and process monitoring in anaerobic digestion and related fields.

5.4 Pretreatment Methods and Physicochemical Modifications

Pretreatment methods are crucial for modifying substrates' physicochemical properties to enhance anaerobic digestion efficiency. These methods aim to increase complex organic materials' biodegradability, improving microbial access and biogas production. Mechanical pretreatments, such as milling and grinding, can enhance biogas yield by up to 60

6 Biogas Production and Applications

6.1 Factors Influencing Biogas Production

Biogas production is shaped by various factors that affect both yield and quality. The composition and ratios of substrates are crucial, with optimal organic loading rates, such as 3.4 kg VS/m^3.d, enhancing yield [5]. Substrate diversity, including agricultural residues and municipal waste, offers significant production opportunities, necessitating strategic selection [17]. Pretreatment methods, such as ultrasonic and microaerobic pretreatment, improve biodegradability and methane yield while reducing chemical and energy inputs [29, 19].

Operational parameters like temperature, pH, and VFA concentrations are pivotal for biogas quality. Dynamic optimization models that regulate VFA concentrations can enhance biohydrogen yield and biogas quality [39]. Advanced modeling techniques, including deep neural networks, offer superior predictive capabilities, improving process control [39]. Thermophilic Microbial Fuel Cell (TMFC) technology provides a promising waste-to-energy conversion method [14]. Machine learning approaches effectively predict adverse events, reducing costs and enhancing maintenance strategies [7]. Complex dynamical behaviors from advanced models, such as bistability and tristability, offer insights into optimizing anaerobic digestion processes [24].

6.2 Technological Advancements in Biogas Production

Recent advancements in biogas production focus on process efficiency and sustainability through innovative methods and materials. The use of non-food feedstocks not only supports biodiesel production but also addresses food security and land use concerns [42]. Innovative purification techniques refine biogas to meet renewable energy standards, enhancing competitiveness with fossil fuels [42]. Valorizing biodigester plant waste into functional materials, such as lignin-derived carbons for supercapacitors and microbial fuel cells, improves energy efficiency and sustainability [34].

Advancements in mathematical modeling have enhanced understanding of microbial interactions, crucial for optimizing biogas production. Models of mutualistic relationships within microbial communities provide insights for improving anaerobic digestion systems [26]. These models support strategies to enhance yield and stability, aligning with broader renewable energy and waste management goals.

6.3 Applications of Biogas as a Renewable Energy Source

Biogas production through anaerobic digestion offers significant potential for renewable energy generation and waste management. As a versatile energy carrier, biogas can be used for electricity, heating, and transportation, reducing fossil fuel dependency and greenhouse gas emissions [43].

Integrating biogas systems into existing infrastructures supports the transition to a bio-based economy, positioning anaerobic digestion as a key electricity source [23].

Using agricultural and municipal waste as feedstocks addresses waste management while providing economic benefits through energy and fertilizer production. This dual benefit underscores the need for policy reforms to promote biogas technology adoption [43]. Biogas systems enhance energy security by offering decentralized solutions tailored to local demands, making them attractive for rural and off-grid communities [9, 12]. Deploying biogas technologies in these areas can stimulate economic development, improve energy access, and promote sustainability.

7 Conclusion

7.1 Challenges and Future Directions

Anaerobic digestion (AD) presents several complex challenges that necessitate focused research to enhance its efficiency and sustainability. The intricate microbial interactions within AD systems remain a significant hurdle, as existing models often fall short in accurately depicting the dynamic nature of these communities, thus limiting their predictive utility. Future research should aim to refine these models by incorporating more detailed interactions and parameters to improve system stability and predictive accuracy. The practical application of these models will depend on their validation against experimental data from operational AD systems.

Optimizing biogas production through pretreatment methods is crucial, especially by fine-tuning ultrasonic parameters and exploring innovative enzymatic solutions. Developing low-energy, cost-effective pretreatment strategies is essential for the economic viability of AD, particularly when processing lignocellulosic biomass. Research should also focus on enhancing co-digestion mixtures and integrating microalgae cultivation to improve sustainability.

Ammonia toxicity poses a significant threat to AD stability, necessitating research into its molecular mechanisms and innovative mitigation strategies. Employing advanced optimization techniques, such as Pareto genetic algorithms and deep neural network models, could significantly improve process optimization. Additionally, advancements in cathode materials and reactor designs are critical for enhancing AD system performance and scalability.

For effective process monitoring and control, integrating sophisticated models that account for varying substrate compositions and microbial interactions is imperative. Advanced monitoring techniques, such as the Unscented Kalman Filter, applied to real measurement data, and the exploration of higher-order AD models with nonlinear output equations are vital for improving predictive accuracy and reliability. Furthermore, optimizing the computational efficiency of turbulent diffusion models and their application in multiphase flow scenarios could greatly enhance the robustness of AD systems.

Addressing these challenges and pursuing these research directions is vital for advancing anaerobic digestion, thereby increasing its role in renewable energy production and sustainable waste management. By prioritizing these areas, the full potential of AD systems can be realized, significantly contributing to global efforts toward sustainable energy solutions and environmental resilience.

References

[1] Stéphane Abanades, H Abbaspour, A Ahmadi, B Das, MA Ehyaei, F Esmaeilion, M El Haj Assad, T Hajilounezhad, DH Jamali, A Hmida, et al. A critical review of biogas production and usage with legislations framework across the globe. *International Journal of Environmental Science and Technology*, pages 1–24, 2022.

[2] Le Chen, Wei Fang, Jianning Chang, Jinsong Liang, Panyue Zhang, and Guangming Zhang. Improvement of direct interspecies electron transfer via adding conductive materials in anaerobic digestion: mechanisms, performances, and challenges. *Frontiers in Microbiology*, 13:860749, 2022.

[3] Raul M. Alonso, Adrian Escapa, Ana Sotres, and Antonio Moran. Integrating microbial electrochemical technologies with anaerobic digestion to accelerate propionate degradation, 2020.

[4] M. J. Wade, R. W. Pattinson, N. G. Parker, and J. Dolfing. Emergent behaviour in a chlorophenol-mineralising three-tiered microbial 'food web', 2015.

[5] Nour El Houda Chaher, Nils Engler, Abdallah Nassour, and Michael Nelles. Effects of co-substrates' mixing ratios and loading rate variations on food and agricultural wastes' anaerobic co-digestion performance. *Biomass Conversion and Biorefinery*, pages 1–16, 2021.

[6] Maria Solé-Bundó, Fabiana Passos, Maycoll S Romero-Güiza, Ivet Ferrer, and Sergi Astals. Co-digestion strategies to enhance microalgae anaerobic digestion: A review. *Renewable and Sustainable Energy Reviews*, 112:471–482, 2019.

[7] Stefano Coniglio, Anthony J. Dunn, and Alain B. Zemkoho. Infrequent adverse event prediction in low carbon energy production using machine learning, 2021.

[8] Shiplu Sarker, Jacob J Lamb, Dag R Hjelme, and Kristian M Lien. A review of the role of critical parameters in the design and operation of biogas production plants. *Applied Sciences*, 9(9):1915, 2019.

[9] Md Mosleh Uddin and Mark Mba Wright. Anaerobic digestion fundamentals, challenges, and technological advances. *Physical Sciences Reviews*, 8(9):2819–2837, 2023.

[10] Ying Jiang, Ewan McAdam, Yue Zhang, Sonia Heaven, Charles Banks, and Philp Longhurst. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. *Journal of Water Process Engineering*, 32:100899, 2019.

[11] Jay N Meegoda, Brian Li, Kush Patel, and Lily B Wang. A review of the processes, parameters, and optimization of anaerobic digestion. *International journal of environmental research and public health*, 15(10):2224, 2018.

[12] Nathaniel Sawyerr, Cristina Trois, Tilahun Workneh, and Vincent Okudoh. An overview of biogas production: Fundamentals, applications and future research. *International Journal of Energy Economics and Policy*, 9(2):105–116, 2019.

[13] Sunil P Lohani and Jouni Havukainen. Anaerobic digestion: factors affecting anaerobic digestion process. In *Waste bioremediation*, pages 343–359. Springer, 2017.

[14] Nicole Jannelli, Rosa Anna Nastro, Viviana Cigolotti, Mariagiovanna Minutillo, and Giacomo Falcucci. Low ph, high salinity: too much for microbial fuel cells?, 2016.

[15] Jeremy Z. Yan, Prashant Kumar, and Wolfgang Rauch. Effect of turbulent diffusion in modeling anaerobic digestion, 2024.

[16] Tewfik Sari and Matthew J. Wade. Generalised approach to modelling a three-tiered microbial food-web, 2015.

[17] Katarzyna Ignatowicz, Gabriel Filipczak, Barbara Dybek, and Grzegorz Wałowski. Biogas production depending on the substrate used: a review and evaluation study—european examples. *Energies*, 16(2):798, 2023.

[18] Helena Junicke. Comment on "a compilation and bioenergetic evaluation of syntrophic microbial growth yields in anaerobic digestion" by patón, m. and rodríguez, j. [water research 162 (2019), 516-517], 2021.

[19] Farrukh Raza Amin, Habiba Khalid, Han Zhang, Sajid u Rahman, Ruihong Zhang, Guangqing Liu, and Chang Chen. Pretreatment methods of lignocellulosic biomass for anaerobic digestion. *Amb Express*, 7:1–12, 2017.

[20] Primitivo B. Acosta-Humánez, Maximiliano Machado-Higuera, and Alexander V. Sinitsyn. A model of anaerobic digestion for biogas production using abel equations, 2016.

[21] Tyler Meadows, Marion Weedermann, and Gail S. K. Wolkowicz. Global analysis of a simplified model of anaerobic digestion and a new result for the chemostat, 2019.

[22] Alain Rapaport, Jan Sieber, Serafim Rodrigues, and Mathieu Desroches. Extremum seeking via continuation techniques for optimizing biogas production in the chemostat, 2013.

[23] Christopher J. K. Knight, Alexandra S. Penn, and Rebecca B. Hoyle. A dynamical model of the industrial economy of the humber region, 2014.

[24] Thamer Hmidhi, Radhouane Fekih-Salem, and Jérôme Harmand. Analysis of anaerobic digestion model with two serial interconnected chemostats, 2024.

[25] Tom Clegg and Thilo gross. Cross-feeding creates tipping points in microbiome diversity, 2024.

[26] Tewfik Sari, Miled El Hajji, and Jérôme Harmand. Analysis of a mathematical model of syntrophic bacteria in a chemostat, 2011.

[27] Antoine Haddon, Hector Ramirez, and Alain Rapaport. Optimal and sub-optimal feedback controls for biogas production, 2019.

[28] Annaliza McGillivray, Abbas Khalili, and David A. Stephens. Estimating sparse networks with hubs, 2020.

[29] Rashid Mustafa Korai, Akiber Chufo Wachemo, Liu Yue, Muhammad Jaffar, Zhengwei Li, Muhammad Shahbaz, Hairong Yuan, and Xiujin Li. Effect of ultrasonic application during koh pretreatment and anaerobic process on digestion performance of wheat straw. *RSC advances*, 10(16):9290–9298, 2020.

[30] Simon Hellmann, Terrance Wilms, Stefan Streif, and Sören Weinrich. Comparison of unscented kalman filter design for agricultural anaerobic digestion model, 2024.

[31] Antoine Picard-Weibel, Gabriel Capson-Tojo, Benjamin Guedj, and Roman Moscoviz. Bayesian uncertainty quantification for anaerobic digestion models, 2024.

[32] Larissa T. Arashiro, Ivet Ferrer, Diederik P. L. Rousseau, Stijn W. H. Van Hulle, and Marianna Garfi. The effect of primary treatment of wastewater in high rate algal pond systems: biomass and bioenergy recovery, 2020.

[33] Kin Tung Michael Ho, Kuan-Cheng Chen, Lily Lee, Felix Burt, Shang Yu, Po-Heng, and Lee. Quantum computing for climate resilience and sustainability challenges, 2024.

[34] Bridget K. Mutuma, Ndeye F. Sylla, Amanda Bubu, Ndeye M. Ndiaye, Carlo Santoro, Alessandro Brilloni, Federico Poli, Ncholu Manyala, and Francesca Soavi. Valorization of biodigestor plant waste in electrodes for supercapacitors and microbial fuel cells, 2021.

[35] D. B. Panaro, M. R. Mattei, G. Esposito, J. P. Steyer, F. Capone, and L. Frunzo. A modeling and simulation study of anaerobic digestion in plug-flow reactors, 2021.

[36] Simon Hellmann, Arne-Jens Hempel, Stefan Streif, and Sören Weinrich. Observability and identifiability analyses of process models for agricultural anaerobic digestion plants, 2023.

[37] Cristina Rodriguez, Abed Alaswad, KY Benyounis, and Abdul G Olabi. Pretreatment techniques used in biogas production from grass. *Renewable and sustainable energy reviews*, 68:1193–1204, 2017.

[38] Angélica M. Alzate Ibañez, Carlos Ocampo-Martinez, Carlos A. Cardona Alzate, and Víctor M. Trejos M. Monitoring management criterion of an anaerobic digester using an explicit model based on temperature and ph, 2017.

[39] Mahmood Mahmoodi-Eshkaftaki, Gustavo Mockaitis, and Mohammad Rafie Rafiee. Dynamic optimization of volatile fatty acids to enrich biohydrogen production using a deep learning neural network, 2022.

[40] Tewfik Sari and Boumediene Benyahia. The operating diagram for a two-step anaerobic digestion model, 2020.

[41] Larissa Terumi Arashiro, Neus Montero, Ivet Ferrer, Francisco Gabriel Acien, Cintia Gomez, and Marianna Garfi. Life cycle assessment of high rate algal ponds for wastewater treatment and resource recovery, 2020.

[42] Arijana Bušić, Semjon Kundas, Galina Morzak, Halina Belskaya, Nenad Marđetko, Mirela Ivančić Šantek, Draženka Komes, Srđan Novak, and Božidar Šantek. Recent trends in biodiesel and biogas production. *Food technology and biotechnology*, 56(2):152, 2018.

[43] Oleg Kucher, Taras Hutsol, Szymon Glowacki, Iryna Andreitseva, Anatolii Dibrova, Andrii Muzychenko, Anna Szeląg-Sikora, Agnieszka Szparaga, and Sławomir Kocira. Energy potential of biogas production in ukraine. *Energies*, 15(5):1710, 2022.

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