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Anaerobic Digestion for Wastewater Treatment: A Review of Principles, Processes and Performance

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Abstract

Anaerobic digestion (AD) is a well-established process used in wastewater treatment to break down organic matter while generating biogas and reducing the amount of sludge produced. This review covers the basic principles of AD, it focuses on the different types of systems used, their performance, and the latest advancements in the field. It highlights key research findings that show how effective AD is in removing pollutants, producing methane, and recovering valuable resources, making it a sustainable option for managing wastewater. The review also discusses ongoing challenges, such as improving reactor designs, boosting microbial activity, and scaling up the technology for larger applications. By offering a clear overview of AD's potential and its limitations, this paper aims to provide practical insights for researchers and engineers looking to make wastewater treatment more efficient and environmentally friendly.

1. Introduction

Anaerobic Digestion (AD) is a microbially mediated process that helps in the conversion of organic matter into biogas (CH_4 and CO_2) and stabilized sludge [1][2][3]. This process has been widely adopted for the treatment of wastewater as a result of its ability to reduce organic loading, produce renewable energy, minimize sludge production, and enhance environmental sustainability [4][5]. Wastewater treatment is a very important process in mitigating environmental pollution caused by human and industrial activities [6][7]. Among various treatment technologies, AD stands out due to its capacity for organic matter degradation, energy recovery in the form of biogas, and its relatively low operational costs compared to aerobic processes. AD is widely applied in municipal wastewater treatment, industrial effluent treatment, and the stabilization of sewage sludge [8].

In the quest for sustainable development, AD has emerged as a pivotal technology in wastewater treatment, aligning with the United Nations' Sustainable Development Goals (SDGs) [9]. This biological process not only mitigates environmental pollution but also transforms organic waste into valuable resources, such as biogas and nutrient-rich fertilizers [10][11]. By effectively managing wastewater through AD, countries can enhance water quality (SDG 6), improve public health (SDG 3), and foster economic opportunities (SDG 1 and SDG 8) through resource recovery. Additionally, AD contributes to environmental sustainability by reducing greenhouse gas emissions and promoting responsible waste management practices (SDGs 11-14) [12][13]. However, the successful implementation of AD technologies requires a comprehensive understanding of the underlying principles, processes, and performance metrics. This review provides an all-inclusive assessment of the principles and mechanisms that make AD effective in treating wastewater, it also provides a detailed evaluation of performance metrics, including pollutant removal efficiencies and biogas yields of the system.

2. Principles of AD

AD is a biological process that occurs in the absence of oxygen, it involves a series of microbiological reactions in which microorganisms break down organic matter [14]. The flow chart for wastewater treatment using AD is presented in Figure 1. The AD process for wastewater treatment, as depicted in flowchart, begins with the pre-treatment of organic wastewater through screening and grit removal, followed by the breakdown of organic matter in an anaerobic digester by microorganisms. This breakdown proceeds through stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, it produces biogas which is composed mainly of methane and carbon dioxide. The biogas is stored and utilized as a renewable energy source, while the remaining solid digestate can be repurposed as a nutrient-rich fertilizer [15][16]. This process not only contributes to effective pollutant removal but also enhances energy recovery and sustainability in wastewater treatment systems [17].

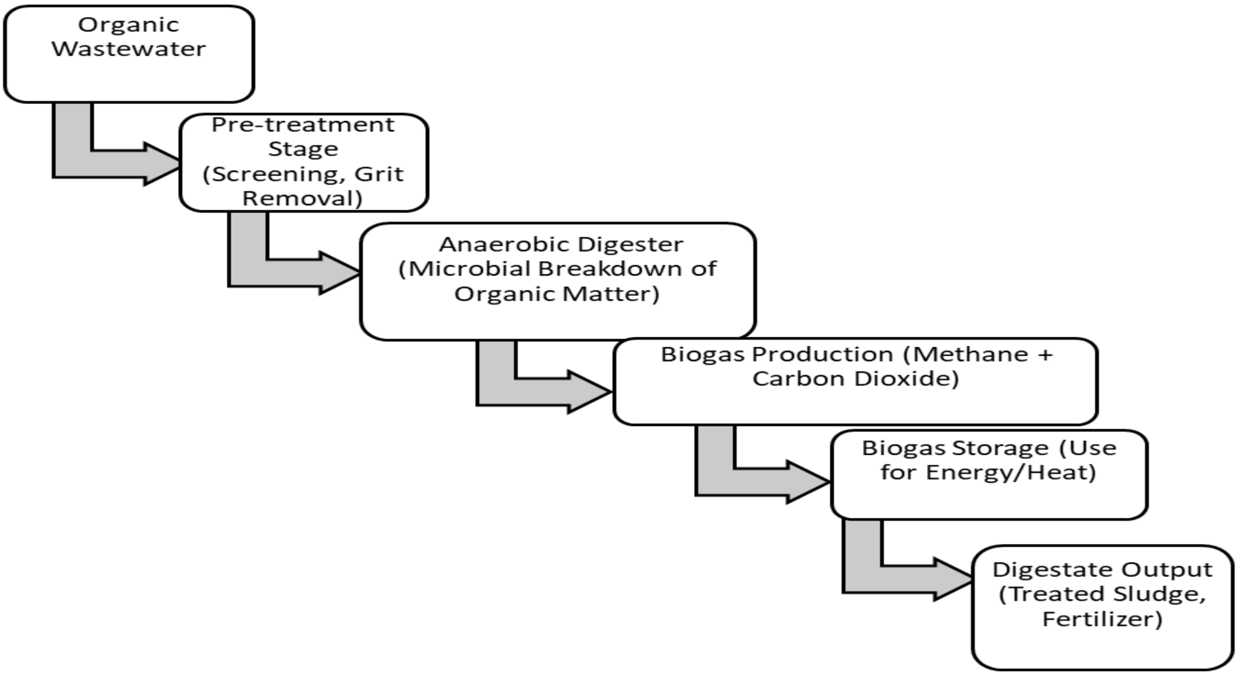

Figure 1: Flow chart for wastewater treatment using AD

2.1 Stages of AD

AD is typically divided into four main stages as depicted in Figure 2. The flowchart illustrates the four sequential stages of AD, which are essential to the wastewater treatment. The decomposition of organic materials and the creation of biogas depend on these phases. Complex organic molecules like proteins, lipids, and carbohydrates are hydrolyzed in the first stage to produce simpler monomers like sugars, amino acids, and fatty acids. Acidogenic bacteria further break down these hydrolysis products during acidogenesis, producing hydrogen, carbon dioxide, ammonia, and volatile fatty acids. Acetogenic bacteria convert volatile fatty acids into acetate, carbon dioxide, and hydrogen during the third stage, known as acetogenesis. Lastly, methanogenic archaea transform hydrogen and acetate into methane (CH_4) and carbon dioxide (CO_2), the main constituents of biogas, during the methanogenesis stage [18][19].

An environmentally friendly method of producing heat or power is to use the biogas generated during AD as a renewable energy source. Furthermore, by reintroducing important nutrients into the soil, the stabilized digestate (the solid residue that remains after digestion) can be used as a nutrient-rich fertilizer, supporting the circular economy [20].

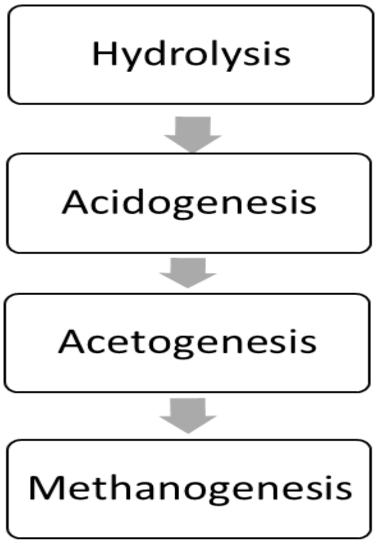

Figure 2: Stages in AD

2.2 AD Reactor Designs

Several reactor designs are commonly employed for AD, including the Continuous Stirred Tank Reactor (CSTR), Upflow Anaerobic Sludge Blanket (UASB), Expanded Granular Sludge Bed (EGSB), and Anaerobic Filter (AF) [21][22]. The CSTR is widely used due to its operational flexibility and simplicity [23]. Different configurations of anaerobic digesters are selected for wastewater treatment based on the specific design and goals of the system [24]. The UASB reactor allows wastewater to pass upward through a sludge blanket, where microorganisms effectively break down organic pollutants, making it suitable for both municipal and industrial wastewater treatment [25]. The Anaerobic Sequencing Batch Reactor (ASBR) operates in batch mode, providing efficient handling of variable organic loads with operational flexibility [26]. Similarly, the EGSB reactor, which is an enhancement of the UASB, operates at higher hydraulic loading rates and retains biomass for longer periods, thereby improving pollutant degradation efficiency [27]. Lastly, the Anaerobic Membrane Bioreactor (AnMBR) combines AD with membrane filtration, allowing for efficient separation of solids and liquids, producing higher-quality effluent and reducing sludge production [28][29][30].

3 Operation Efficiency of AD

3.1 Operating Parameters

Optimal operating parameters are essential for the efficient performance of AD in wastewater treatment. These include temperature, pH, retention time, and organic loading rate (OLR). AD can be conducted under mesophilic conditions (30-37°C) for greater microbial stability or thermophilic conditions (50-60°C), which enhance the degradation rate but may lead to instability and higher energy consumption [31][32][33]. The ideal pH range is between 6.5 and 8.5, as fluctuations outside this can inhibit methanogenic bacteria and reduce methane production. Hydraulic retention time (HRT) typically ranges from 10 to 30 days, allowing sufficient time for the breakdown of organic matter, though longer HRTs increase reactor size and costs [34]. The organic loading rate (OLR), usually between 1 to 10 kg/m^3/day, must be carefully monitored to avoid overloading the system, which can lead to acid accumulation and process failure. Balancing these parameters ensures stable operation, maximizes biogas production, and enhances overall treatment efficiency [35][36][37].

3.2 Treatment Efficiency

AD is recognized for its ability to efficiently treat various types of wastewater, principally in removing organic pollutants and pathogens [5]. The high removal rates of key parameters such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), and pathogens underline its suitability for sustainable wastewater management [38]. AD has been shown to demonstrate high treatment efficiency in wastewater management, achieving high efficiency in COD removal, BOD removal, TSS removal, and pathogen reduction [39][40]. These removal efficiencies demonstrate AD's effectiveness in breaking down organic pollutants and enhancing effluent quality. By effectively reducing these key parameters, AD not only mitigates environmental pollution but also promotes sustainability and resource recovery in wastewater treatment systems [41][42].

3.3 Performance of AD in Wastewater Treatment

The effectiveness of AD in treating wastewater is typically assessed through several key metrics. First, pollutant removal efficiency is a primary indicator, with AD achieving high removal rates for organic matter, including COD and BOD as well as significant reductions in nitrogen and phosphorus levels [43][44]. This capacity to eliminate harmful pollutants not only improves effluent quality but also ensures compliance with environmental regulations. Additionally, the process is evaluated based on methane production, as biogas yields are closely linked to the organic load and specific operating conditions. The methane content in biogas typically demonstrates AD's role as a valuable source of renewable energy [45]. Energy efficiency is another critical aspect, as AD enables energy recovery from wastewater, ultimately reducing the overall energy demand of wastewater treatment plants [46][47]. Finally, the environmental benefits of AD cannot be overlooked; by significantly reducing greenhouse gas emissions and providing an alternative to fossil fuel usage, AD emerges as a sustainable technology that contributes to environmental conservation and resource recovery in wastewater management [48][49]. Together, these factors affirm the comprehensive effectiveness of AD as a superior method for wastewater treatment.

4. Application of AD in wastewater treatment

A number of studies have been conducted on the application of AD in wastewater treatment. Table 1 summarizes key findings from some studies on anaerobic wastewater treatment systems. The table highlights their effectiveness in treating different types of waste and producing biogas. The systems investigated include UASB reactors, anaerobic membranes, and thermophilic digesters, with results demonstrating high COD removal rates, methane production, energy savings, and the potential for sustainable industrial wastewater management.

Table 1: Researchers and Findings on AD for Wastewater Treatment

Researcher(s)	Year	System	Key Findings
[50]	2022	UASB Reactor	Evaluated a full-scale UASB reactor in Ghana, and highlighted the UASB reactor's potential as an effective and sustainable wastewater management solution for developing countries. It revealed satisfactory performance with 93% COD and 98% BOD removal rates, with methane content averaging 64.7%.
[51]	2024	UASB Reactor	Verified that a low-cost anaerobic pretreatment notably improved the performance of a UASB reactor in treating synthetic vinasse. The COD (Chemical Oxygen Demand) removal efficiency rose from 80.45% to 88.4%, while methane production saw a significant boost, increasing from 56% to 62.5%, indicating its potential as an effective and economical solution for reducing vinasse-related environmental pollution on an industrial scale.
[52]	2024	Anaerobic Membranes	Proved that a combined system using an AnMBR together with an anoxic/oxic membrane bioreactor effectively treats natural rubber industry wastewater, achieving over 98% COD reduction, significant removal of ammonia (72.9%), total nitrogen (72.8%), and total phosphorus (71.3%), while highlighting the importance of specific bacterial genera and revealing insights into membrane fouling dynamics, thus showcasing its potential for sustainable industrial wastewater management.
[53]	2017	ASBR Reactor	Established that a pilot-scale ASBR effectively treats tannery wastewater, achieving COD removal efficiencies of 69–85% and methane yields of 0.17–0.30 m^3/kg COD removed, with optimal performance at an organic loading rate of 1.03 kg m^{-3} d^{-1}, which could potentially reduce greenhouse gas emissions by 1,500 to 3,032 tons CO_2-equivalent per year, highlighting the ASBR's potential for sustainable wastewater management in the tanning industry.
[54]	2022	Hybrid Anaerobic	Demonstrated that the AnMBR significantly outperforms the UASB in treating swine wastewater, achieving approximately 90% COD removal compared to around 60% for UASB, higher methane yields (0.23 L/g-COD), and enhanced energy recovery, while also promoting a more favorable microbial community structure that facilitates the degradation of refractory organic matter and broadens methanogenesis pathways.
[55]	2021	High-Rate Digesters	Found that anaerobic wastewater treatment plants (WWTP) achieve over 50% electricity savings compared to aerobic systems, with anaerobic systems consuming 0.43 kWh/m^3 versus 1.02 kWh/m^3 for aerobic plants, and further potential energy savings of 16-42% could be realized by fully implementing AD across the WWTPs.
[56]	2023	Thermophilic AD	Established that stepwise acclimatization of waste activated sludge in a thermophilic anaerobic fixed-bed biofilm reactor significantly improved methane production and system stability at ultrahigh organic loading rates in food waste treatment, with enhanced microbial diversity and efficient waste-to-energy conversion.
[57]	2024	Co-Digestion	Demonstrated that dry AD using a combination of activated sludge and plant waste at carbon-to-nitrogen C/N ratios of 30, 25, and 20 effectively produces biogas and fertilizer, with the C/N ratio of 25 yielding the highest biogas volume and meeting standards for waste treatment and methane production.

5. Advancements and Challenges

Advancements in AD technology have significantly improved its application in wastewater treatment, while challenges persist in scaling up and optimizing the process for practical use [58]. One major advancement is co-digestion [59][60][61], where wastewater is treated alongside organic wastes such as food waste or agricultural residues [62]. This practice has been shown to enhance biogas yield and improve the efficiency of anaerobic digesters by providing a more balanced feedstock, which leads to greater methane production and energy recovery [62]. Microbial community analysis has also advanced, offering a deeper understanding of the microbial consortia involved in each stage of the AD process [63][64][65]. Technologies like high-throughput sequencing have allowed researchers to identify and manipulate specific microbial populations to optimize digestion performance and stability under varying environmental conditions [66][67]. This has led to better control over the anaerobic process by reducing downtime and enhancing reactor resilience to fluctuations in organic load or temperature.

6. Conclusion

AD remains a highly effective and sustainable technology for wastewater treatment that offers significant advantages such as pollutant removal, biogas production, and energy recovery. The advancements in reactor designs, microbial analysis, and co-digestion techniques have enhanced the efficiency and scalability of AD systems, making them more adaptable to various waste streams and operational conditions. Despite these advancements, challenges remain in optimizing the process for large-scale implementation, particularly in maintaining system stability and managing high organic loads. However, with ongoing research and technological innovations, AD holds substantial promise for addressing global wastewater management needs while contributing to environmental sustainability and energy conservation.

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