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# Reviewing the potential of anaerobic membrane bioreactors in wastewater treatment

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## Abstract

Anaerobic membrane bioreactors (AnMBRs) represent an innovative approach to wastewater treatment, combining anaerobic digestion with membrane filtration to achieve efficient organic pollutant removal and resource recovery. This review critically examines the potential of AnMBRs in wastewater treatment, highlighting their principles, advantages, challenges, recent advancements, and future prospects. AnMBRs offer several advantages over traditional aerobic treatment methods, including higher organic loading rates, reduced energy requirements, and biogas production through methane generation. However, challenges such as membrane fouling, reactor complexity, and operational costs have limited their widespread adoption. Recent advancements in membrane materials, fouling mitigation strategies, and process optimization have improved AnMBR performance and feasibility. Novel membrane materials with enhanced fouling resistance and durability have been developed, while innovative cleaning techniques and operational protocols have been implemented to mitigate membrane fouling and prolong membrane lifespan. Process optimization strategies, including reactor design modifications and operational parameter adjustments, have enhanced treatment efficiency and reduced energy consumption in AnMBRs. Future research directions in AnMBR technology focus on optimizing reactor configurations, exploring novel membrane materials and fouling control strategies, and conducting comprehensive techno-economic assessments to evaluate the environmental and economic sustainability of AnMBRs. Integration of AnMBRs with emerging technologies such as membrane distillation, forward osmosis, and bioelectrochemical systems holds promise for further enhancing treatment performance and resource recovery capabilities. Additionally, addressing knowledge gaps in membrane fouling mechanisms, microbial community dynamics, and long-term system stability is crucial for advancing AnMBR technology and facilitating its widespread implementation in wastewater treatment. Overall, AnMBRs offer significant potential for sustainable wastewater treatment, providing opportunities for organic pollutant removal, energy recovery, and resource reuse. By addressing technical challenges, optimizing process parameters, and conducting interdisciplinary research, AnMBRs can contribute to the development of efficient, cost-effective, and environmentally friendly wastewater treatment solutions, ultimately supporting the goal of achieving cleaner water resources and a more sustainable future.

**Keywords:** Potential; Anaerobic; Membrane; Bioreactors; Wastewater Treatment

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## 1. Introduction

Anaerobic membrane bioreactors (AnMBRs) have emerged as a novel and promising technology in the field of wastewater treatment, offering a unique combination of anaerobic digestion and membrane filtration processes. This introduction provides an overview of AnMBRs, underscores the significance of exploring their potential in wastewater treatment, and outlines the purpose and scope of this review (Elmoutez, et. al., 2023, Maaz, et. al., 2019, Vinardell, et. al., 2020). Anaerobic membrane bioreactors (AnMBRs) are advanced wastewater treatment systems that integrate anaerobic digestion with membrane filtration technology. In AnMBRs, microorganisms degrade organic pollutants in the absence of oxygen, generating biogas as a byproduct, while membrane filtration selectively retains solids, microorganisms, and dissolved contaminants. This synergistic combination enables efficient removal of organic pollutants, pathogens, and nutrients from wastewater, producing high-quality effluent suitable for discharge or reuse.

The exploration of AnMBRs in wastewater treatment is of paramount importance due to several compelling reasons. Firstly, AnMBRs offer distinct advantages over traditional aerobic treatment methods, including higher organic loading rates, reduced energy consumption, and biogas production for renewable energy generation. Additionally, AnMBRs have the potential to minimize sludge production and offer opportunities for resource recovery, such as biogas utilization and nutrient recycling. Given the increasing pressures on water resources, coupled with the need for sustainable and cost-effective wastewater treatment solutions, the investigation of AnMBRs holds significant promise for addressing these challenges (Anjum, et. al., 2021, Guo, et.al., 2020, Lee & Liao, 2021).

The purpose of this review is to critically examine the potential of Anaerobic Membrane Bioreactors (AnMBRs) in wastewater treatment. It aims to provide a comprehensive analysis of AnMBR technology, including its principles, advantages, challenges, recent advancements, and future research directions. By synthesizing existing literature and discussing key findings, this review seeks to contribute to the understanding of AnMBRs and their role in advancing sustainable wastewater treatment practices. Furthermore, it aims to inform researchers, practitioners, and policymakers about the opportunities and challenges associated with AnMBRs, facilitating informed decision-making and promoting the adoption of this innovative technology in wastewater treatment applications.

## 2. Principles of Anaerobic Membrane Bioreactors

Anaerobic membrane bioreactors (AnMBRs) represent an innovative approach to wastewater treatment that integrates anaerobic digestion with membrane filtration. This section provides a detailed exploration of the principles underlying AnMBRs, including an explanation of anaerobic digestion, an introduction to membrane filtration in AnMBRs, and an analysis of the synergistic benefits derived from combining these processes.Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen. This process occurs naturally in environments such as wetlands, marshes, and anaerobic wastewater treatment systems. In the context of wastewater treatment, anaerobic digestion is utilized to treat organic pollutants present in wastewater streams, converting them into biogas (mainly methane and carbon dioxide) and residual biomass (Hu, et. al., 2020, Hu, et. al., 2022, Robles, et. al., 2021).

Complex organic compounds present in wastewater are hydrolyzed into simpler soluble compounds by extracellular enzymes produced by anaerobic microorganisms. The hydrolyzed compounds are further metabolized by acidogenic bacteria, producing volatile fatty acids (VFAs), hydrogen (H2), and carbon dioxide (CO2) as intermediate products. Acetogenic bacteria convert VFAs and other intermediates into acetic acid, hydrogen, and carbon dioxide through acetogenesis (Kong, et. al., 2019, Rani, et. al., 2019, Soh, et. al., 2020). Methanogenic archaea utilize the acetic acid, hydrogen, and carbon dioxide produced in previous steps to generate methane (CH4) and carbon dioxide (CO2) as final products. Overall, anaerobic digestion is a complex biochemical process that relies on the synergistic activity of diverse microbial communities to degrade organic pollutants and produce biogas. Membrane filtration is a physical separation process that utilizes semi-permeable membranes to selectively retain suspended solids, microorganisms, and dissolved contaminants while allowing water molecules to pass through. In AnMBRs, membrane filtration is employed to separate treated wastewater from residual biomass, suspended solids, and contaminants generated during anaerobic digestion.

The main types of membranes used in AnMBRs include microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) membranes, with pore sizes ranging from tens of micrometers to nanometers. These membranes are typically made from materials such as polymeric polymers (e.g., polyethylene, polypropylene), ceramic, or metallic materials, depending on the specific application requirements and operating conditions.Membrane filtration in AnMBRs operates under a variety of configurations, including submerged, external, and sidestream configurations. In submerged AnMBRs, membranes are immersed directly in the bioreactor tank, while in external and sidestream configurations, membranes are located outside the bioreactor tank and connected to it via recirculation loops (Arabi, et. al., 2020, Khanzada, et. al., 2020, Yang, et. al., 2020).

The integration of anaerobic digestion with membrane filtration in AnMBRs offers several synergistic benefits that enhance wastewater treatment efficiency and resource recovery: Anaerobic digestion effectively degrades organic pollutants present in wastewater, producing soluble metabolites and gases. Membrane filtration selectively retains suspended solids and microorganisms, ensuring high-quality effluent with low levels of organic contaminants. Anaerobic digestion generates biogas (mainly methane and carbon dioxide) as a byproduct of organic matter degradation. Membrane filtration separates biogas from treated wastewater, allowing for its collection and utilization as a renewable energy source for heat and power generation. Anaerobic digestion promotes the conversion of organic matter into biogas and residual biomass, resulting in lower sludge production compared to aerobic treatment methods. Membrane filtration further concentrates residual biomass, reducing the volume of sludge generated and facilitating its dewatering and disposal (Kamali, et. al., 2019, Kamsonlian, et. al., 2021, Zhang, X. (2022).

Anaerobic digestion and membrane filtration enable the recovery of valuable resources from wastewater, including biogas, nutrients (e.g., nitrogen, phosphorus), and water. Biogas can be utilized for energy production, while nutrients can be recycled for agricultural or industrial applications. Moreover, treated water can be reused for non-potable purposes such as irrigation, industrial processes, or groundwater recharge. Overall, the synergistic combination of anaerobic digestion and membrane filtration in AnMBRs offers a sustainable and efficient approach to wastewater treatment, providing opportunities for organic pollutant removal, energy recovery, sludge reduction, and resource reuse. By harnessing the complementary benefits of these processes, AnMBRs contribute to the development of environmentally friendly and economically viable solutions for wastewater management and resource recovery (Bohra, et. al., 2022, Robles, et. al., 2021, Zacharof, et. al., 2019).

## 3. Advantages of Anaerobic Membrane Bioreactors

Anaerobic membrane bioreactors (AnMBRs) offer a range of advantages over traditional aerobic treatment methods, making them an increasingly attractive option for wastewater treatment applications. This section delves into the key advantages of AnMBRs, including their higher organic loading rates, reduced energy requirements, potential for reduced sludge production, and resource recovery opportunities. One of the significant advantages of AnMBRs is their ability to handle higher organic loading rates (OLRs) compared to aerobic treatment methods. Anaerobic digestion processes in AnMBRs are not limited by the availability of oxygen, allowing microorganisms to metabolize organic pollutants at a faster rate. As a result, AnMBRs can treat wastewater with higher concentrations of organic matter, such as industrial effluents or high-strength municipal sewage, without experiencing process inhibition or system overload (Bohra, et. al., 2022, Robles, et. al., 2021, Zacharof, et. al., 2019).

The higher OLRs achievable in AnMBRs translate into smaller reactor footprints and lower capital costs per unit of treated wastewater. This makes AnMBRs particularly suitable for applications where space constraints or land availability pose challenges to conventional aerobic treatment systems. Additionally, the compact design of AnMBRs allows for modular and scalable configurations, facilitating ease of installation, operation, and maintenance. AnMBRs offer significant energy savings compared to aerobic treatment methods, primarily due to the anaerobic digestion process's lower energy demand (Abdelrahman,et. al., 2021, Chen, Liu & Huang, 2020, Hu, et. al., 2022). Anaerobic microorganisms metabolize organic pollutants in the absence of oxygen, yielding energy-rich biogas (mainly methane and carbon dioxide) as a metabolic byproduct. This biogas can be captured and utilized as a renewable energy source for heat and power generation, thereby offsetting operational energy requirements and reducing overall energy consumption.

The biogas produced in AnMBRs has the potential to meet a substantial portion of the facility's energy needs, including heating digesters, powering membrane aeration systems, or supplying electricity to onsite equipment. (Ardakani & Gholikandi, 2020, Calise, et. al., 2021, Milani & Bidhendi, 2023) By harnessing biogas for energy recovery, AnMBRs contribute to sustainability goals by reducing reliance on fossil fuels and mitigating greenhouse gas emissions associated with conventional wastewater treatment processes. Another advantage of AnMBRs is their potential for reduced sludge production compared to aerobic treatment methods. Anaerobic digestion promotes the conversion of organic matter into biogas and residual biomass, resulting in lower sludge yields and higher sludge stabilization rates. This can lead to significant cost savings and environmental benefits associated with sludge handling, dewatering, and disposal (Calabria, 2019, Jain, 2020, Pikaar, et. al., 2022).

The reduced sludge production in AnMBRs reduces the volume of biosolids generated, minimizing the need for sludge treatment and disposal facilities. This can result in lower operational costs, reduced environmental impacts, and improved overall system sustainability. Additionally, the residual biomass produced in AnMBRs is often more stable and less odorous than aerobic sludge, making it easier to handle and manage. AnMBRs offer opportunities for resource recovery from wastewater, including the extraction of valuable products such as biogas, nutrients, and water. Biogas produced during anaerobic digestion can be captured and utilized as a renewable energy source for heating, power generation, or transportation fuels. This not only reduces operational energy costs but also contributes to greenhouse gas mitigation and climate change mitigation efforts (Dagnew & Parker, 2021, Guo, et. al., 2024, Hu, et. al., 2022).

Furthermore, AnMBRs enable the recovery of nutrients such as nitrogen and phosphorus from wastewater, which can be recycled and reused as fertilizers or soil amendments in agricultural or landscaping applications. By capturing and recycling nutrients from wastewater, AnMBRs contribute to nutrient cycling, resource conservation, and sustainable agriculture practices. Additionally, AnMBRs allow for the recovery of treated water suitable for non-potable reuse applications, such as irrigation, industrial processes, or groundwater recharge. By reclaiming and reusing treated water, AnMBRs support water conservation efforts, reduce reliance on freshwater resources, and mitigate the environmental impacts associated with wastewater discharge.

In conclusion, Anaerobic Membrane Bioreactors (AnMBRs) offer several advantages over traditional aerobic treatment methods, including higher organic loading rates, reduced energy requirements, potential for reduced sludge production, and resource recovery opportunities. By harnessing the synergistic benefits of anaerobic digestion and membrane filtration, AnMBRs provide sustainable and cost-effective solutions for wastewater treatment, contributing to environmental protection, resource conservation, and energy efficiency in the quest for cleaner water resources and a more sustainable future.

## 4. Challenges Associated with Anaerobic Membrane Bioreactors

Despite their numerous advantages, anaerobic membrane bioreactors (AnMBRs) also face several challenges that must be addressed to realize their full potential in wastewater treatment applications. This section discusses the key challenges associated with AnMBRs, including membrane fouling and fouling control strategies, reactor design complexity, and operational costs and economic feasibility. Membrane fouling is one of the most significant challenges encountered in AnMBRs, leading to reduced filtration efficiency, increased energy consumption, and shortened membrane lifespan (Anjum, et. al., 2021, De Vela, 2021, Hu, et. al., 2020). Membrane fouling occurs when suspended solids, microbial biomass, and organic matter accumulate on the membrane surface or within its pores, obstructing flow and impeding filtration performance. Factors contributing to membrane fouling in AnMBRs include the presence of colloidal and soluble organic matter, microbial growth, and operational conditions such as hydraulic shear, temperature, and pH (El Batouti, M., Alharby, N. F., & Elewa, M. M. (2021, Peters, et. al., 2021, Zhao, et. al., 2022).

To mitigate membrane fouling in AnMBRs, various fouling control strategies have been developed and implemented, Pre-treatment processes such as screening, sedimentation, and coagulation-flocculation can remove larger particles and colloidal matter from the influent wastewater, reducing the potential for membrane fouling. Periodic chemical cleaning of membranes using agents such as acids, alkalis, and oxidizing agents can dissolve and remove foulants accumulated on the membrane surface, restoring filtration performance. Surface modification techniques such as hydrophilic coatings, graft polymerization, and membrane surface roughening can alter membrane surface properties to reduce fouling propensity and enhance fouling resistance. Backwashing involves reversing the flow direction through the membrane to dislodge and remove foulants from the membrane surface. Intermittent or continuous backwashing can help maintain membrane permeability and prevent fouling buildup (Gul, Hruza & Yalcinkaya, 2021, Khan & Kim, 2023, Kucera, 2019).

Despite these fouling control strategies, membrane fouling remains a persistent challenge in AnMBRs, requiring ongoing research and innovation to develop more effective and sustainable fouling mitigation techniques. The design and operation of AnMBRs are inherently more complex than traditional aerobic treatment systems, requiring careful consideration of factors such as hydraulic retention time, sludge retention time, membrane configuration, and aeration strategy. The integration of anaerobic digestion with membrane filtration introduces additional complexity, as both processes must be optimized to ensure efficient organic pollutant removal, biogas production, and membrane filtration. The design complexity of AnMBRs poses challenges related to system scalability, process stability, and operational flexibility. Achieving optimal reactor performance requires balancing conflicting objectives such as maximizing biogas production while minimizing membrane fouling, optimizing hydraulic conditions while ensuring sufficient biomass retention, and integrating pre-treatment processes while maintaining overall system reliability.

Furthermore, the selection and sizing of membranes, pumps, valves, and other components must be carefully coordinated to meet hydraulic and treatment requirements while minimizing capital and operating costs. Additionally, the integration of advanced process control and monitoring systems is essential to optimize AnMBR performance, detect operational issues, and implement corrective actions in real-time. Despite their potential benefits, AnMBRs are associated with higher capital and operational costs compared to conventional aerobic treatment methods, primarily due to the cost of membranes, energy consumption, and maintenance requirements. The purchase and installation of membrane modules represent a significant upfront investment, while ongoing operational expenses include energy for aeration, membrane cleaning, and chemical treatment, as well as labor and maintenance costs.

The economic feasibility of AnMBRs depends on several factors, including wastewater characteristics, treatment objectives, regulatory requirements, and local energy and labor costs. While AnMBRs offer potential savings in terms of reduced sludge disposal costs, biogas production, and resource recovery opportunities, these benefits must be weighed against the higher initial capital investment and operational expenses. To enhance the economic feasibility of AnMBRs, ongoing research and development efforts are focused on reducing membrane costs, improving membrane performance and durability, optimizing process configurations, and increasing energy efficiency. Additionally, techno-economic assessments and life cycle cost analyses are essential for evaluating the long-term economic viability of AnMBRs and informing investment decisions (Arias, Feijoo & Moreira, 2020, Gao, et. al., 2021, Gukelberger, et. al., 2019).

In conclusion, anaerobic membrane bioreactors (AnMBRs) face several challenges that must be addressed to realize their full potential in wastewater treatment applications. Membrane fouling, reactor design complexity, and operational costs represent significant hurdles that require ongoing research and innovation to develop effective mitigation strategies and enhance system performance. By addressing these challenges, AnMBRs can become more efficient, cost-effective, and sustainable solutions for wastewater treatment, contributing to environmental protection, resource recovery, and water quality improvement initiatives.

## 5. Recent Advancements in Anaerobic Membrane Bioreactors

Anaerobic membrane bioreactors (AnMBRs) represent an innovative approach to wastewater treatment, offering efficient removal of organic pollutants while enabling resource recovery. In recent years, significant advancements have been made in AnMBR technology to overcome challenges such as membrane fouling, enhance treatment efficiency, and improve energy recovery. This section discusses three key areas of recent advancements in AnMBRs: the development of novel membrane materials with enhanced fouling resistance, innovative fouling mitigation strategies and cleaning techniques, and process optimization for improved treatment efficiency and energy recovery (Ding, et. al., 2022, Huang, Jeffrey & Pidou, 2023, Vinardell, et. al., 2020).

Membrane fouling is a major challenge in AnMBRs, leading to decreased filtration efficiency and increased energy consumption. Recent advancements in membrane technology have focused on developing novel membrane materials with enhanced fouling resistance to mitigate fouling-related issues. These advanced membranes exhibit improved hydrophilicity, anti-fouling properties, and mechanical strength, allowing for longer membrane lifespans and reduced maintenance requirements. (De Vela, 2021, Nabi, et. al., 2023)

One example of a novel membrane material is the incorporation of zwitterionic polymers or nanoparticles into membrane matrices to enhance fouling resistance. These materials possess both positive and negative charges, repelling foulants and preventing their adhesion to the membrane surface. Additionally, surface modification techniques such as grafting, coating, and blending have been employed to alter membrane surface properties and improve fouling resistance. Other approaches to enhancing membrane fouling resistance include the development of asymmetric membrane structures, which feature a dense top layer for filtration and a porous support layer for mechanical stability (Lau & Yong, 2021, Rahimi & Mahdavi, 2019, Sun, et. al., 2019). These asymmetric membranes offer improved flux rates and fouling resistance compared to traditional homogeneous membranes.

Furthermore, the use of nanomaterials such as graphene oxide, carbon nanotubes, and nanocomposites has shown promise in enhancing membrane performance and durability in AnMBRs. These nanomaterials possess unique properties such as high surface area, mechanical strength, and chemical stability, making them suitable for applications in harsh wastewater environments. Overall, the development of novel membrane materials with enhanced fouling resistance represents a significant advancement in AnMBR technology, offering opportunities to improve system reliability, reduce maintenance costs, and enhance treatment efficiency (Amiri, et. al., 2022, Li, et. al., 2020, Shiri, Hashemifard & Abdi, 2023).

In addition to developing fouling-resistant membrane materials, recent advancements in AnMBRs have focused on innovative fouling mitigation strategies and cleaning techniques to maintain membrane performance and prolong membrane lifespan. These strategies aim to prevent fouling formation, remove foulants from the membrane surface, and restore membrane permeability. One innovative fouling mitigation strategy is the implementation of dynamic membrane systems, which utilize periodic membrane vibration or oscillation to dislodge foulants and prevent their accumulation on the membrane surface. This dynamic membrane cleaning approach has been shown to improve fouling resistance and reduce energy consumption in AnMBRs.

Another fouling mitigation strategy involves the use of biofilm-forming microorganisms to coat the membrane surface and create a protective layer that inhibits foulant attachment. These biofilm-coated membranes exhibit enhanced fouling resistance and improved long-term stability, leading to reduced membrane fouling and lower maintenance requirements. Furthermore, advancements in membrane cleaning techniques have focused on developing environmentally friendly and cost-effective cleaning agents that effectively remove foulants without damaging the membrane surface. These include enzymatic cleaning agents, biodegradable surfactants, and green solvents that target specific foulant types while minimizing environmental impact (Ahmed, Amin & Mohamed, 2023, Gizer, et. al., 2023, Jadhav, et. al., 2021).

Additionally, the integration of online monitoring and control systems enables real-time monitoring of membrane fouling dynamics and proactive adjustment of operating parameters to mitigate fouling formation. This allows for timely intervention and optimization of AnMBR performance, leading to improved treatment efficiency and reduced energy consumption. Overall, innovative fouling mitigation strategies and cleaning techniques represent significant advancements in AnMBR technology, offering opportunities to enhance system reliability, reduce maintenance costs, and improve treatment performance.

In addition to membrane-related advancements, recent research in AnMBRs has focused on process optimization strategies to improve treatment efficiency and energy recovery. These strategies aim to optimize reactor design, operating conditions, and process configurations to maximize organic pollutant removal, biogas production, and resource recovery. One area of process optimization is the design and configuration of AnMBR systems to enhance mixing, biomass retention, and mass transfer within the reactor. This includes the use of innovative reactor geometries, improved membrane module configurations, and optimized hydraulic conditions to minimize dead zones, promote biomass growth, and maximize contact between wastewater and microorganisms.

Furthermore, advancements in anaerobic digestion kinetics modeling and reactor modeling have enabled more accurate prediction of system performance and optimization of operating parameters such as hydraulic retention time, organic loading rate, and temperature. This allows for precise control of anaerobic digestion processes and optimization of biogas production and organic pollutant removal efficiency. Additionally, advancements in membrane module design and membrane bioreactor configuration have focused on enhancing energy recovery from biogas production and reducing energy consumption for membrane aeration. This includes the development of energy-efficient membrane modules, optimization of membrane aeration strategies, and integration of biogas utilization systems for heat and power generation.

Moreover, advancements in sensor technology, automation, and control systems enable real-time monitoring and optimization of AnMBR performance, allowing for adaptive control strategies that respond to dynamic changes in influent wastewater quality, membrane fouling, and process conditions. Overall, process optimization for improved treatment efficiency and energy recovery represents a critical area of advancement in AnMBR technology, offering opportunities to enhance system performance, reduce operating costs, and improve overall sustainability (Frontistis, Lykogiannis & Sarmpanis, 2023, Wang, et. al., 2023, Zhu, et. al., 2021).

In conclusion, recent advancements in anaerobic membrane bioreactors (AnMBRs) have focused on addressing key challenges such as membrane fouling, enhancing treatment efficiency, and improving energy recovery. The development of novel membrane materials with enhanced fouling resistance, innovative fouling mitigation strategies and cleaning techniques, and process optimization for improved treatment efficiency and energy recovery represent significant advancements in AnMBR technology. By integrating these advancements into AnMBR design and operation, it is possible to achieve more reliable, efficient, and sustainable wastewater treatment solutions, ultimately contributing to environmental protection, resource recovery, and water quality improvement initiatives.

## 6. Future Research Directions

Anaerobic membrane bioreactors (AnMBRs) hold immense promise for sustainable wastewater treatment, offering efficient organic pollutant removal and resource recovery. However, several challenges and opportunities remain to be addressed to further advance AnMBR technology (Aslam, Khan & Shahzad, 2022, Maaz, et. al., 2019, Zhen, et. al., 2019). This section discusses key future research directions for AnMBRs, including the optimization of reactor configurations and operational parameters, exploration of novel membrane materials and fouling control strategies, comprehensive techno-economic assessments to evaluate sustainability and feasibility, and the integration of AnMBRs with emerging technologies for enhanced performance.

Optimizing reactor configurations and operational parameters is essential for maximizing AnMBR performance and efficiency (De Vela, 2021, Elmoutez, et. al., 2023, Yurtsever, Basaran & Ucar, 2020). Future research should focus on exploring different reactor designs, such as submerged, external, and sidestream configurations, to determine the most suitable configuration for specific wastewater characteristics and treatment objectives. Additionally, the optimization of operational parameters such as hydraulic retention time, organic loading rate, temperature, and pH can significantly impact AnMBR performance. Furthermore, advancements in modeling and simulation techniques can aid in optimizing reactor configurations and operational parameters by predicting system behavior, identifying potential bottlenecks, and guiding process optimization strategies. By integrating advanced modeling tools with experimental data, researchers can develop predictive models that facilitate the design, operation, and control of AnMBR systems for optimal performance.

The development of novel membrane materials with enhanced fouling resistance is crucial for overcoming membrane fouling challenges in AnMBRs (Ewuzie, et. al., 2022, Mustapha, et. al., 2023, Nwuzor, et. al., 2021). Future research should focus on exploring innovative membrane materials, such as nanocomposites, nanocomposite coatings, and biomimetic membranes, that exhibit improved fouling resistance, mechanical strength, and durability. Additionally, the investigation of membrane surface modification techniques, including surface coatings, grafting, and functionalization, can further enhance fouling resistance and prolong membrane lifespan. Moreover, research efforts should continue to explore novel fouling control strategies and cleaning techniques to maintain membrane performance and mitigate fouling-related issues. This includes the development of dynamic membrane cleaning systems, biofilm-forming microorganisms, and environmentally friendly cleaning agents that effectively remove foulants while minimizing membrane damage and energy consumption.

Comprehensive techno-economic assessments are essential for evaluating the sustainability and feasibility of AnMBRs and guiding investment decisions. (Mahmud, et. al., 2021, Mahmud, 2022, Nowrouzi & Abyar, 2021) Future research should focus on conducting life cycle assessments (LCAs) and techno-economic analyses (TEAs) to assess the environmental impacts, economic viability, and social acceptability of AnMBR systems compared to conventional wastewater treatment technologies. These assessments should consider various factors, including capital and operational costs, energy consumption, resource recovery potential, greenhouse gas emissions, and regulatory compliance. By integrating environmental, economic, and social indicators, researchers can develop holistic sustainability metrics that capture the overall performance and impact of AnMBRs on society and the environment.

Furthermore, techno-economic assessments can help identify critical cost drivers, optimize system design and operation, and identify opportunities for cost reduction and process optimization. By evaluating the long-term economic viability and sustainability of AnMBRs, decision-makers can make informed investment decisions and prioritize research and development efforts to maximize the benefits of AnMBR technology. Integration of AnMBRs with emerging technologies offers opportunities to enhance system performance, improve treatment efficiency, and expand resource recovery capabilities. Future research should focus on exploring synergies between AnMBRs and technologies such as membrane distillation, forward osmosis, electrochemical processes, and microbial electrochemical systems to achieve enhanced nutrient removal, energy recovery, and water reuse (Kobos, et. al., 2020, Mahmud, et. al., 2021, Shokri & Fard, 2023).

Additionally, the integration of sensor technology, automation, and control systems can enable real-time monitoring and optimization of AnMBR performance, allowing for adaptive control strategies that respond to dynamic changes in influent wastewater quality, membrane fouling, and process conditions. Overall, future research directions for AnMBRs should prioritize optimization of reactor configurations and operational parameters, exploration of novel membrane materials and fouling control strategies, comprehensive techno-economic assessments to evaluate sustainability and feasibility, and integration with emerging technologies for enhanced performance. By addressing these research priorities, it is possible to advance AnMBR technology and realize its full potential as a sustainable and cost-effective solution for wastewater treatment.

## 7. Conclusion

Anaerobic membrane bioreactors (AnMBRs) offer a promising approach to wastewater treatment, combining anaerobic digestion with membrane filtration to achieve efficient organic pollutant removal and resource recovery. This review has highlighted the significant advancements, challenges, and future research directions in AnMBR technology, emphasizing its potential to revolutionize wastewater treatment practices.

Throughout this review, several key findings have emerged regarding the potential of AnMBRs in wastewater treatment. First, AnMBRs demonstrate superior organic loading rates, reduced energy requirements, and potential for resource recovery compared to conventional aerobic treatment methods. Second, advancements in membrane materials, fouling control strategies, and process optimization have addressed key challenges such as membrane fouling, reactor design complexity, and operational costs. Third, comprehensive techno-economic assessments and integration with emerging technologies have highlighted the sustainability and feasibility of AnMBRs as a viable wastewater treatment solution.

The findings of this review have significant implications for wastewater treatment practices. AnMBRs offer a sustainable and cost-effective alternative to conventional aerobic treatment methods, providing opportunities for enhanced organic pollutant removal, energy recovery, and resource reuse. By adopting AnMBR technology, wastewater treatment facilities can improve treatment efficiency, reduce environmental impact, and achieve compliance with stringent regulatory requirements. Furthermore, the integration of AnMBRs with emerging technologies and comprehensive techno-economic assessments can inform investment decisions and guide the implementation of sustainable wastewater treatment solutions.

To further advance AnMBR technology and facilitate its widespread adoption, several recommendations for future research and implementation efforts are proposed. First, continued research is needed to optimize reactor configurations, operational parameters, and membrane materials to maximize AnMBR performance and efficiency. Second, comprehensive techno-economic assessments should be conducted to evaluate the sustainability and feasibility of AnMBRs in diverse wastewater treatment settings. Third, efforts should focus on integrating AnMBRs with emerging technologies such as membrane distillation, forward osmosis, and electrochemical processes to enhance treatment efficiency and resource recovery capabilities.

Additionally, collaboration between researchers, industry stakeholders, and policymakers is essential to overcome barriers to implementation, facilitate technology transfer, and promote knowledge sharing. By prioritizing research efforts, fostering interdisciplinary collaboration, and engaging stakeholders, AnMBR technology can be effectively translated into practice, leading to widespread adoption and significant advancements in wastewater treatment practices.

In conclusion, the review of the potential of Anaerobic Membrane Bioreactors in wastewater treatment underscores their importance as a sustainable and efficient solution for organic pollutant removal and resource recovery. By addressing key challenges, leveraging technological advancements, and fostering collaboration, AnMBRs have the potential to revolutionize wastewater treatment practices and contribute to environmental sustainability and public health protection.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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