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Membrane Technology for Energy Saving: Principles, Techniques, Applications, Challenges, and Prospects

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Membrane technology emerges as a transformative solution for global challenges, excelling in water treatment, gas purification, and waste recycling. This comprehensive review navigates the principles, advantages, challenges, and prospects of membrane technology, emphasizing its pivotal role in addressing contemporary environmental and sustainability issues. The goal is to contribute to environmental objectives by exploring the principles, mechanisms, advantages, and limitations of membrane technology. Noteworthy features include energy efficiency, selectivity, and minimal environmental footprint, distinguishing it from conventional methods. Advances in nanomembranes, organic porous membranes, and metal-organic frameworks-based membranes highlight their potential for energy-efficient contaminant removal. The review underscores the integration of renewable energy sources for eco-friendly desalination and separation processes. The future trajectory unfolds with next-gen nanocomposite membranes, sustainable polymers, and optimized energy consumption through electrochemical and hybrid approaches. In healthcare, membrane technology reshapes gas exchange, hemodialysis, biosensors, wound healing, and drug delivery, while in chemical industries, it streamlines organic solvent separation. Challenges like fouling, material stability, and energy efficiency are acknowledged, with the integration of artificial intelligence recognized as a progressing frontier. Despite limitations, membrane technology holds promise for sustainability and revolutionizing diverse industries.

1. Introduction

Rapid industrialization, urbanization, and population growth have placed unprecedented strain on energy resources, leading to concerns about energy security.[1] Global energy consumption has been on a persistent upward trajectory, with the International Energy Agency (IEA) projecting a 27% increase in energy demand by 2040. The proportion of carbon emissions attributed to the energy system is expected to surge from its current 10% to a projected 27% by the year 2050.[2] Against the backdrop of startling statistics, nations worldwide are grappling with an ever-increasing energy demand, dwindling fossil fuel reserves, and the imperative to combat climate change.[1,3] These challenges necessitate a paradigm shift in energy production, distribution, and consumption. Innovative technologies have emerged as indispensable tools in addressing these formidable challenges. Among these, membrane technology emerges as a versatile and highly promising solution, positioned to play a pivotal role in the global pursuit of enhanced energy efficiency and sustainability.[4]

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Membrane technology encompasses a wide spectrum of separation methods that rely on semipermeable membranes, enabling the selective separation of various components within fluid mixtures.[5] The versatility of membrane technology is reinforced by its capacity to adapt to a multitude of sectors. It has surpassed its earlier limitation to niche applications and now plays a significant role in expansive industrial processes, as well as emerging domains like water treatment, healthcare, and the production of renewable energy.[6] Whether applied to seawater desalination or the purification of gases and liquids, membrane technology presents efficient and sustainable answers to diverse industrial challenges.[7] This adaptability positions membrane technology as a pivotal approach for fostering eco-friendly and sustainable manufacturing practices.

Conventional separation methods like distillation and crystallization have long been recognized for their high energy consumption and adverse environmental impacts. In contrast, membrane technology serves as an exemplar of energy-efficient separation practices. At its core, it operates on the principle of selectively allowing specific components to pass through a membrane, contingent upon factors such as size, charge, or chemical properties. This inherent selectivity leads to a reduction in energy consumption, diminished emissions, and increased product purity, making membrane technology an essential instrument for realizing sustainability objectives. By substantially reducing the energy requirements in separation processes across diverse industries, such as petrochemicals, pharmaceuticals, and the food and beverage sector, membrane technology not only preserves valuable resources but also plays a crucial role in mitigating the global energy crisis. Its capability to improve energy efficiency, diminish environmental impacts, and promote sustainability aligns with the pressing necessity to transition toward cleaner and more efficient energy utilization.

In this comprehensive review manuscript, we provide a thorough understanding of membrane technology's principles, mechanisms, advantages, and limitations, fostering a deeper appreciation for its role in addressing the energy crisis and advancing sustainability. We delve into the mechanisms and principles underpinning membrane technology, including membrane structure, transport mechanisms, and performance factors. Additionally, we discuss the technology's energy efficiency, selectivity, and low environmental impact while also addressing challenges like membrane fouling and cost concerns. We explore prospects, emerging trends, and potential applications from environmental remediation to healthcare, highlighting the critical challenges that must be overcome to fully realize the transformative potential of membranes. As we delve deeper into this review, we further explore how membrane technology's unique attributes position it as a critical player in addressing the pressing energy challenges of our time. Ultimately, we summarize the key parameters discussed herein, underlining the significance of membrane technology in the energy sector and proposing future research directions.

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2. Membrane Technologies for Energy-Saving

Membrane technology stands as a pivotal player in the realm of energy-saving technologies. Its applications span a wide spectrum, impacting various sectors such as water treatment, gas separation, and fuel cells. Membrane-based processes have the remarkable ability to significantly reduce energy consumption compared to traditional methods. For instance, in desalination processes, membranes allow for the efficient removal of salt and impurities from seawater, requiring less energy than conventional thermal methods. Additionally, gas separation membranes enable the capture of valuable gases like hydrogen and methane from industrial processes, aiding in energy recovery and reducing emissions. One approach to enhance sustainability in membrane technology involves using biodegradable polymers and nontoxic solvents for membrane production, replacing non-biodegradable petroleum-based materials and hazardous solvents. Additional strategies include recycling membrane components, minimizing preparatory steps to reduce energy usage and waste, reusing waste brine or sludge, incorporating antifouling features to minimize waste, and harnessing energy from waste materials.[8] While the range of their applications is extensive, this section describes some specific uses of these membranes in energy saving via various environmentally friendly applications, including their applications in water treatment, organic solvent recovery, the removal of pharmaceutical and therapeutic contaminants, and gas separation.

2.1. Water Treatment and Desalination

Addressing the global challenge of diminishing freshwater resources, especially in developing nations, requires effective solutions. Desalination and wastewater treatment stand out as vital methods to ensure a safe and ample water supply, considering the vast water reserves in oceans and the continuous generation of wastewater.[9] Among these solutions, membrane separation systems have gained prominence for water purification, desalination, and wastewater treatment.[10] Desalination focuses on removing inorganic salts, while wastewater treatment involves eliminating heavy metals, organic dyes, pesticides, and oily substances along with inorganic salts. Common membrane processes include microfiltration, ultrafiltration, nanofiltration (NF), reverse osmosis (RO), pervaporation, membrane distillation, and electrodialysis.[10c] To enhance separation efficiency, membranes are designed with smaller pores, necessitating higher pressure. Traditionally, synthetic polymers like polyvinylidence fluoride (PVDF), polyacrylonitrile (PAN), and polyethersulfone have been the norm. However, growing environmental concerns are driving a shift toward biodegradable alternatives such as polyhydroxyalkanoates, polylactic acid (PLA), polybutylene succinate, as well as natural materials like cellulose, alginate, chitosan, chitin, lignin, collagen, and sericin.[11] While biocompatible membranes were commercialized as early as the 1960s, they were overshadowed by synthetic polymers due to challenges in their production. However, the current focus on environmental sustainability and reduced reliance on fossil fuels has revitalized interest in green membrane technology, which shows promise across various applications. Advancements in cost-effective, efficient, and scalable technologies have made large-scale water treatment with membranes a practical reality. For example, Han et al.[12] developed ultrathin graphene NF membranes (22–53 nm thick) on microporous substrates. These membranes exhibited 20–60% retention of ionic salts (0.02 M) following the Donnan exclusion principle, with the retention order being $Na_2SO_4 > NaCl > MgSO_4 > MgC_{l2}$, along with a complete rejection of organic dyes. Remarkably, only 34 mg of reduced graphene oxide was used to produce a m^2 of the membrane, signaling a new era of supply-conserving and cost-effective technology for water purification.

In RO systems, the most substantial contributor to energy consumption and operating costs arises from the need to pressurize the feed using high-pressure pumps. The salinity of wastewater increases as seawater inflow and infiltration rise, resulting in a higher base case energy consumption. However, the percentage increase in energy consumption is mitigated by the mixing of high-salinity flows.[13] The forward osmosis (FO)-RO membrane, which does not require a turbine or energy recovery unit, provides dual membrane filtration of impaired feed streams versus conventional RO membranes, thereby reducing the energy required for RO and improving the retention of seawater contaminants. Attarde et al.[14] compared the energy efficiencies of RO-PRO and FO-RO hybrid systems at the same 50% RO recovery rate, and an increase in dilution of the PRO/FO subsystem reduced the energy consumption of the RO-PRO membrane treatment (31% savings). Li et al.[15] used a hollow fiber membrane RO system with high permeability ($7\ L\ m^{-2}\ h^{-1}\ bar^{-1}$) to treat 400 ppm brackish water consuming only $0.197\ kWh\ m^{-3}$ per unit of energy, which is a 65.1% reduction in energy consumption. This study resulted in significant energy savings for seawater below the 2000 ppm salt concentration range.

In the 1980s, energy recovery devices (ERDs) were introduced to RO systems to capture and reuse energy, effectively pressurizing the incoming feed and thus reducing the overall energy consumption of the system.[16] Wang et al.[17] concurred that aside from membrane permeability, the inefficiencies of pumps and ERD had the most significant impact on specific energy consumption. Increasing the feed water pressure and temperature also has a significant positive effect on water recovery. For instance, Koutsou et al.[18] reported that a high feedwater temperature reduces the total energy consumption due to viscosity and flow friction losses. However, it also increases the osmotic pressure and leakage rate, resulting in the degradation of ERD performance. This energy loss is particularly prominent in seawater RO systems, which typically operate at low recovery rates of 35–45% and require higher applied pressures. ERD helped Arabian Potash Company's RO desalination plant reduce energy consumption by 47–53.8% and helped reduce atmospheric CO_2 gas emissions.[19] Mansour et al.[20] added ERDs to make use of the high-pressure brine released from the membrane retention stream, which could improve plant performance and save up to 80% in power consumption. The first generation of ERDs used in RO systems were centrifugal, featuring devices such as Francis turbines, Pelton wheels, and turbochargers. However, these early ERDs had limited capacity and efficiency levels below 80%. A notable advancement came with the introduction of isobaric ERDs, including piston-type work exchangers and rotary pressure exchangers. These innovations offered unlimited capacity and achieved efficiencies as high as 98%. Consequently, RO systems benefited from energy savings of up to 40% due to this significant technological leap.[16] Jamil et al.[21] introduced an isobaric pressure exchanger to replace the conventional ERDs and throttling valves on the brine streams to upgrade the desalination plant capacity, which facilitates a further reduction of 24% of the energy consumption and 50–60% of the second law efficiency. Since there is no physical piston between the seawater flow and the concentrated brine flow in the pipeline, rotating ERDs are considered to be upgraded devices that can achieve very high energy recovery efficiencies.[22] Lou et al.[23] found that the integrated energy recovery and pressurization device taught to reduced electrical energy consumption by 25.7% compared to a conventional ERD and achieved a maximum energy recovery efficiency and mixing rate of 91.3% and 4.97%, respectively, for the desalination process by rationally setting the rotor conduit displacement.

The declining cost of renewable energy technologies, particularly photovoltaic (PV) systems,[24] has propelled advancements in combining renewable energy with desalination methods. To reduce the energy consumption of RO, one approach is hybridization with complementary processes, potentially lowering the cost of PV-powered RO. These integrated systems aim to cut carbon emissions, offering a sustainable and efficient energy supply solution. Currently, there is a growing emphasis on integrating renewable energy sources with hybrid and multihybrid desalination technologies.[16] Among them, an autonomous hybrid wind turbine-PV battery was utilized in Saudi Arabia to power a desalination project.[25] Wu et al.[26] proposed a hybrid PV/diesel system to optimize the RO system, which can significantly reduce greenhouse gas (GHG) emissions compared to a single diesel system and is cost-effective and environmentally friendly. The feasibility of a PV-RO system depends on the availability of the solar resource, the demand for the RO system, the characteristics of the water, and the policies of the local government. Giwa and Hasan[27] increased the economic value of freshwater production by 460–480% by extracting thermal energy from molten salt through a thermosiphon that can concentrate solar energy. PV-powered RO has reached a technologically mature and commercially available stage. The overall cost of this system is closely tied to the energy consumption of its individual components.[28]

Similarly, solar thermal energy, being an economical renewable heat source, holds potential for membrane distillation hybrid systems.[29] In such systems, the cost of heat supply significantly impacts overall energy efficiency. Despite challenges like seasonal energy supply and the additional cost of storage batteries, integrating renewable energy sources with hybrid desalination technologies promises an avenue toward energy-efficient desalination. However, further optimization of the specific energy consumption for hybrid desalination systems and renewable energy sources should be conducted through both modeling and experimental studies before considering their commercial viability.

2.2. Integrated Membrane Technologies and Microbial Fuel Cells (MFCs) for Energy Savings

MFCs represent an eco-friendly technology that serves a dual purpose by treating wastewater while generating energy. Biocompatible polymeric membranes have been instrumental in facilitating proton transfer (H^+) between the two electrodes of MFCs.[30] Biopolymers like chitosan and alginate, known for their inherent hydrophilic properties, are flexible and can be tailored to meet specific requirements for MFCs, such as low proton conductivity and methanol permeability, akin to nafion membranes.[31] Moreover, mixed matrix membranes (MMMs) based on biopolymers offer distinct advantages over pristine membranes. For instance, Cabello et al.[32] studied the influence of pectin, a green polymer electrolyte, on chitosan-pectin membranes. They noted an enhancement in methanol permeability for the MMM at $1.51 \times 10^{-6}\,cm^2\,s^{-1}$ compared to pure chitosan membranes, which had a methanol permeability of $4.24 \times 10^{-6}\,cm^2\,s^{-1}$. MFC could achieve electrical energy conversion efficiencies up to 16% higher than conventional anaerobic treatment.[33] In a study, it was found that a hybrid proton exchange membrane developed by Lee et al.[34] with a 1:1 blend of chitosan and alginate could achieve a power generation of $115\,mW\,m^{-2}$ (with a current density of $333\,mA\,m^{-2}$), which sufficiently enhances the power generation performance of the MFC by a factor of 2.1. In addition, the ratio between biopolymers affects the ionic cross-linking of the composite membrane, and the increase in alginate improves the adsorption and cation exchange capacity of the chitosan membrane. Since poly(R)-3-hydroxybutyrate (PHB) has good in vivo ion permeability and biodegradability making it to be considered as a good material for MFC, Olayiwola Sirajudeen et al.[35] utilized a composite membrane generated by combining a medium-chained poly(R)-3-hydroxyfatty-acid ester with PHB to exhibit better proton transport, maximum voltage potential, and power density.

Additionally, the synergy between MFCs and algae or cyanobacteria can significantly enhance both energy generation and wastewater remediation.[36] These microorganisms play a crucial role in promoting bacterial growth at the anode, enabling oxygen supply through photosynthesis, and removing nitrogen and phosphorus from wastewater.[36] The integration of membrane systems into this bioremediation process offers significant advantages for harvesting algal biomass, extracting lipids or unused nutrients, and facilitating downstream processing of valuable products such as biofuels. Notably, Kumar et al.[37] published a comprehensive review focusing on membrane-integrated green approaches for the simultaneous production of biofuels and value-added co-products from wastewater using algae-based methods. The authors highlighted the following key findings: first, the utilization of wastewater nutrients can replace expensive raw materials and chemicals, enabling cost-effective and large-scale cultivation of microalgal biomass while simultaneously facilitating bioremediation, toxic metal removal, and CO_2 sequestration. Second, membrane-based systems offer a cost-effective and straightforward approach to harvesting algal biomass, lipid extraction, and the separation of valuable products. Third, utilizing membrane systems for downstream separation of fatty acid methyl ester mixtures enables the retention of unreacted oil, recovery of unused alcohol, and glycerol separation, enhancing cost-efficiency. Furthermore, membrane-based separation and purification of fatty acid methyl ester mixtures can yield biodiesel meeting American Society for Testing and Materials standards at a lower cost and with a reduced environmental footprint.

Microalgae-microbial assemblages are effective tools for the development of beneficial microbial communities, and the heterotrophic interactions between microalgae and ectoproducing bacteria promote microalgae-based MFCs (MMFCs) to work with minimal energy inputs, which contributes to the power generation efficiency of MFCs. As a result, MMFCs exhibit higher efficiency in recovering charged energy than conventional MFCs, with MMFCs with maximum power point tracking obtaining 12.9% energy yield, producing bioelectricity that effectively reduces electricity consumption in wastewater treatment applications and improves biological sustainability.[38] Higher biomass concentrations enhance bacterial cell metabolic activity and electron release for power generation in the MFC. Increasing the microalgal biomass concentration by 316.7% in a study by Ndayisenga et al.[39] enhanced the current density by $0.94\,A\,m^{-2}$ (62.1%). Biofilms using algae make the MFC more diverse and better able to cope with toxic inputs or operational stagnation. Christwardana et al.[40] found that *Saccharomyces cerevisiae*-assisted MMFCs could attain a voltage of 0.17 V and a current density of 400 mA m, resulting in a 137.75% increase in power density compared to conventional MFC. Additionally, it led to an enhanced treatment of wastewater biomass by microalgae. Suspension of *Saccharomyces cerevisiae* in MMFCs was found to be effective in boosting the power generation of stationary yeast MMFCs by 10.8%.[41] Moreover, the design of the integrated photobioreactor adjusts the light intensity and nutrient supply, thus allowing the generation of higher energy content through algal biomass conversion than direct MFC power generation. However, there remain areas for improvement, such as enhancing lipid profiles, ensuring the long-term stability of algal products during extraction, and advancing the commercialization of various valuable products. Future studies also need to address the high cost of infrastructure and the high energy requirements for microalgae harvesting.

An additional avenue for conserving energy and resources in water purification involves utilizing green membranes constructed primarily with live biomass rather than relying on bio-derived polymers. A recent innovative approach by Eggensperger et al.[42] showcased the development of living filtration membranes using a symbiotic culture of bacteria and yeast cultivated on green kombucha tea. This ultrafiltration membrane exhibited a remarkable pure water flux of $135 \pm 25\,L\,m^{-2}\,h^{-1}\,bar^{-1}$ and high efficiency in rejecting polypropylene and gold nanoparticles, achieving a rejection rate of approximately 90%. Furthermore, the living microbial cells within the membranes possessed the unique ability to self-regenerate in the event of damage facilitated by the production of new cellulose fibers. This healing capability was observed under a confocal microscope, demonstrating the growth of microbes and the restoration of the membrane in the affected area. The development of bacterial cellulose membrane materials reduces the energy consumption of gravity-driven separations and also broadens the application of the separations.[43] These green membranes are not only cost-effective but also environmentally friendly, as they can be customized using readily available and sustainable materials, representing a promising direction for creating affordable and eco-friendly water purification membranes.

In summary, membrane systems play a pivotal role in wastewater treatment and desalination processes. Sustainable membrane technologies are essential for water treatment, whether as standalone solutions or complementary processes. Further research is strongly recommended to address factors that impact the economics and performance of membrane systems, including membrane fouling, water flux, and overall sustainability.

2.3. Contaminants Removal

The use of membrane systems is increasingly favored for efficiently separating synthesized products and chemical contaminants from reaction mixtures. This approach offers high productivity and low energy consumption, diverging from the labor-intensive and expensive traditional methods, such as chromatography, distillation, and extraction. Furthermore, these conventional techniques may have adverse effects on overall process efficiency.[44] Synthesized products, ranging from personal care items to pharmaceuticals and pesticides, have become significant in modern society. However, their improper management can pose environmental and health risks. Traditional treatment techniques like activated carbon adsorption and advanced oxidation processes frequently encounter issues related to efficiency, cost, and environmental impact. Membranes have emerged as a promising solution due to their notable attributes, such as high selectivity, permeability, and low energy usage. For instance, a comprehensive analysis involving 158 pesticides demonstrated promising results with commercial RO.[45] Pesticides pose a formidable challenge when it comes to their removal from water sources, given their intricate composition. Furthermore, the integration of membrane technologies with other biological or chemical approaches holds the potential to unlock novel opportunities in water treatment. However, addressing all the concerns associated with micropollutants, as mentioned earlier, can be effectively tackled through the adoption of a sustainable, eco-friendly, and environmentally conscious strategy centered around membrane-based technology.[46]

One noteworthy environmentally friendly membrane variant is the membrane bioreactor (MBR) system, which integrates biological treatment with membrane filtration to yield high-quality effluent. This synergistic approach bolsters the biological treatment process by retaining microorganisms and preventing washout, rendering MBR systems highly effective in the removal of various synthesized products, including antibiotics, hormones, and personal care items.[47] Anaerobic membrane (AnMBR) wastewater treatment has gained recognition as a low-energy, prospective substitute for the traditional, energy-intensive activated sludge technique.[48] Harclerode et al.[49] compared the energy efficiency of AnMBR for the removal of sulfides from wastewater and determined that chemical coagulation facilitated the energy recovery of AnMBR (-0.08 to $0.28\,\text{kWh m}^{-3}$). The configuration of MBR significantly influences its energy consumption. Arefi-Oskoui et al.[50] found that submerged MBRs, with their minimal equipment demands, consume only 1/25 to 1/10 of the energy compared to sidestream MBRs. The large-scale production and fabrication of advanced membrane elements will necessitate improving the individual treatment capabilities of MBRs. Additionally, the development of innovative contaminant removal methods and membrane contamination analysis, based on precise automatic control of aeration strategies, will be crucial to further reduce the energy consumption of MBRs.[51]

NF membranes represent another noteworthy green membrane technology, effectively removing small organic molecules like pesticides and pharmaceuticals through electrostatic interactions and size exclusion. Their high selectivity and efficiency make NF membranes a favorable alternative for energy-saving wastewater and water treatment.[52] The feasibility of selectively recovering lithium from NF membranes has been demonstrated in a recent study by Gao et al.[53] They utilized DK270 membranes with a strong positive surface charge, small pore size, and robust acid resistance, effectively retaining and recovering 99% and 40.1% of lithium ions. NF exhibits promising applications in precision separation, offering unique advantages such as low energy consumption for ions and small molecules. Wafi et al.[54] found that NF membranes were effective in reducing power consumption by 29% ($0.134\,\text{m}^3\,\text{kWh}^{-1}$) compared to RO membranes ($0.095\,\text{m}^3\,\text{kWh}^{-1}$).

RO membranes, operating on size exclusion and electrostatic interactions, efficiently remove various chemical contaminants, including volatile organic compounds, heavy metals, and persistent organic pollutants. Egea-Corbacho Lopera et al.[55] successfully removed novel contaminants (caffeine, theobromine, theophylline, amoxicillin, and penicillin G) using BW30-2540 RO membranes. For neutral contaminants, the impact of membrane affinity is crucial, and at low permeate fluxes, RO membranes exhibit higher passage rates for neutral hydrophilic microcontaminants.[56] In the future, bigger membrane elements, multistage RO, or tighter membranes may be used to attain higher removal efficiencies. Membrane distillation processes, which use temperature gradients to separate chemical contaminants from water, also offer a sustainable approach.[57] Membrane distillation has been found to increase 100-fold the concentration of nickel at 60 °C and further reduce the thermal energy consumption in the recovery of nickel through a combined chemical precipitation/electrodeposition process.[58] In addition, for the removal of heavy metals, Shaheen et al.[59] developed the first photothermal air-gap membrane distillation system with a high retention factor that retained 97% of the heavy metals and provided an important basis for sustainable and efficient membrane distillation for energy supply.

The necessity to remove chemical contaminants and synthesized products from reaction mixtures is fundamental to the continuous progress of various processes. For instance, in acetone-butanol-ethanol fermentation, it is imperative to recover butanol to maintain the fermentation process, which is aimed at biofuel production to address energy and environmental concerns. In the fermentation process, when the butanol concentration exceeds a specified threshold (>60 wt%), it necessitates the continuous removal of butanol from the fermented broth. Currently, vaporized butanol can be effectively separated from the mixture without compromising productivity using pervaporation, a method that relies on temperature and pressure gradients to drive the butanol through a membrane.[60] The nanocomposite membranes developed for this purpose are constructed from a polymer with intrinsic microporosity and functionalized carbon black nanoparticles, which enhance membrane hydrophobicity, resistance to swelling, and separation efficiency compared to pristine polymer membranes.[61] These hybrid membranes also hold promise for constructing membrane reactors that can directly extract butanol from fermentation broth.

MMMs often offer economic benefits and flexibility in polymer selection. The incorporation of inorganic materials, such as nanoparticles of metal-organic frameworks (MOFs) or covalent-organic frameworks (COFs), provides both mechanical strength and high selectivity.[4b] Numerous nanocomposite green membranes have been tailored for the dehydration of alcoholic beverages or the reduction of alcohol content, resulting in the production of more desirable, relatively healthier low-alcohol beverages while preserving other organoleptic compounds. For instance, Msahel et al.[62] recently explored an innovative approach to enhance selectivity and reduce energy consumption in membrane-based separation processes. They synthesized environmentally friendly MOF materials and integrated them with biopolymer PLA to create a novel MMM for separating azeotropic methanol/methyl tert-butyl ether (MeOH/MTBE) mixtures through pervaporation. This novel MMM exhibited a remarkable 22% improvement in selectivity compared to pristine PLA membranes. The efficient separation of MTBE, crucial for enhancing gasoline octane levels, required the removal of unreacted methanol. By employing microwave-assisted hydrothermal synthesis, they successfully synthesized spherical MOFs (MIL-100 Fe) with a total pore volume of $0.96\,cm^3\,g^{-1}$. These MOFs played a pivotal role in enhancing methanol selectivity by creating preferential pathways and modifying membrane properties such as mechanical strength, wettability, and swelling behavior. The cost-effective and eco-friendly fabrication process offers a wealth of possibilities for developing energy-efficient membrane separation systems.

2.4. Gas Purification

Hydrogen (H_2), as a clean and sustainable energy carrier, plays a crucial role in mitigating environmental concerns. In industrial hydrogen production, it's essential to purify the produced hydrogen due to the presence of unwanted gases. Emerging porous organic polymers (POPs) with consistent pore structures and adjustable pore sizes offer a promising solution to fine-tune permeability-selectivity relationships in molecular sieving. POP-based membranes can be easily functionalized with diverse chemical or physical properties, enabling tailored gas separation applications. This includes the purification of H_2 from other gases due to its smaller kinetic diameter, as well as the separation of hydrocarbon gases like methane from N_2 or CO_2, supporting cleaner and more cost-effective feedstock gases for industrial use.[63] However, it is widely acknowledged that POPs-based membranes generally exhibit lower selectivity compared to MOF-derived membranes, which can precisely adjust their pore sizes according to the kinetic diameter of hydrogen molecules (0.289 nm). This discrepancy is exemplified by a pioneering study conducted by Lu et al.[64] where they created a COF/Al_2O_3 composite membrane. The 3D COF-320 membrane displayed relatively modest separation factors, with values of 3.7 for H_2/N_2 and 2.8 for H_2/CH_4. Following this, a thorough computational investigation assessed the potential of COF-derived membranes for gas separation by considering electron density overlaps. While monolayer CTF-0-based membranes exhibited exceptionally high selectivity in permitting H_2 to pass through various gas mixtures, the experimental results indicated lower separation factors compared to theoretical values. This difference could potentially be attributed to the increased thickness of the experimental COF-based membranes compared to monolayer COF membranes.[65] These advancements in membrane technology are vital for enhancing the efficiency of hydrogen purification and its role in clean energy applications, contributing to energy savings and environmental preservation.

Fu et al.[66] embarked on an innovative project to synthesize a COF/MOF combined membrane designed for gas separation, with a primary focus on enhancing the selectivity of H_2/CO_2 gas mixtures. The process involved the use of a polyaniline-coated SiO_2 disk as a support for the initial fabrication of a COF-300 membrane through a solvothermal method. Subsequently, one side of the SiO_2 disk-grown COF-300 underwent treatment in a dimethylformamide solution containing zinc nitrate hexahydrate, terephthalic acid, and 1,4-diazabicyclo[2.2.2]octane under heating to facilitate the growth of a MOF layer on top of the presynthesized COF layer. This composite membrane demonstrated superior selectivity for the H_2/CO_2 gas mixture than distinct COF and MOF membranes, achieving a superior separation factor of 12.6. In a subsequent development, they constructed a 2D COF layer on the previously synthesized MOF layer to create a COF-MOF composite membrane.[67] Using a similar synthetic approach with slight modifications, UiO-66 was initially synthesized on the PANI-coated SiO_2 disk. Subsequently, H2P-DHPh COF, obtained through the polycondensation of 5,10,15,20-tetrakis(4-aminophenyl)porphyrin and 2,5-dihydroxyterephthalaldehyde, was grown on top of the MOF layer. This COF/MOF composite membrane outperformed their previous work, achieving an impressive separation factor of up to 32.9 for the H_2/CO_2 gas mixture, surpassing the Robeson upper bound.

Another innovative composite membrane was developed by Fan et al.[68] capitalizing on both COFs and MOFs for exceptional hydrogen separation with high selectivity. They incorporated ZIF-67 structures into the TpPa-1 membrane they synthesized by facilitating their growth within the confined COF pores. The resulting composite membrane, known as ZIF-67-in-TpPa-1 and supported by α-Al_2O_3, displayed a consistent, dense, and defect-free surface. This membrane excelled in H_2 separation from equimolar gas mixtures, showcasing higher separation selectivity than the single TpPa-1 membrane. It achieved remarkable separation factors of 33.3, 34.9, 192.7, and 110.5 for H_2/CH_4, H_2/CO_2, C_3H_8, and H_2/C_3H_6, respectively. Fan et al.[69] also introduced a novel approach involving the layer-by-layer growth of COF films, incorporating two types of COFs with different pore sizes to create interlaced pore networks, thereby enhancing H_2 separation selectivity. The process began with the fabrication of COF-LZU-1 on an NH_2-modified Al_2O_3 substrate, followed by the deposition of ACOF-1 with a smaller pore size on the COF-LZU-1 surface. Scanning electron microscopy confirmed the subsequent creation of the ACOF-1 and COF-LZU1 layers. Gas separation tests conducted on H_2/N_2, H_2/CO_2, and H_2/CH_4 gas mixtures demonstrated impressive separation factors for the bilayer membrane, reaching 83.9, 24.2, and 100.2, respectively. These advancements in composite membrane technology hold promise for enhancing gas separation processes, contributing to energy efficiency and environmental benefits.

Separating different hydrocarbons in industrial processes is particularly challenging because unsaturated and saturated hydrocarbons often share very similar physicochemical properties and closely matched kinetic diameters. Some authors ingeniously combined TpPa-1 with styrene-butadiene rubber (SBR) polymer to create COF-MMMs with different SBR and TpPa-1 ratios using the dip-coating method.[70] Notably, the resulting MMM, containing 50 wt% TpPa-1, exhibited remarkable reverse selectivity for $C_3H_6/N_2$and C_3H_8/N_2, with values of 20 and 15, respectively. In a recent development, ionic liquids containing Ag^+ were introduced into COF membranes to improve the capacity for ethane/ethylene separation.[71] In this novel method, a mixture consisting of an ionic liquid solution and an aqueous silver nitrate solution was applied to the TpPa-SO_3H membrane that had been synthesized. The membrane was then subjected to vacuum drying in preparation for subsequent testing. Gas permeation experiments were conducted using gas mixtures containing propylene/propane (50:50 vol%) and ethylene/ethane (50:50 vol%). The incorporation of an ionic liquid containing silver ions resulted in the creation of a confinement layer, effectively reducing the nanochannel size within the membrane. This reduction was key to enhancing ethylene permeance through primary confinement effects. By carefully adjusting the channel size to 0.87 nm through the Ag^+-IL modification, the membrane demonstrated outstanding separation performance. Specifically, it achieved an impressive ethylene/ethane selectivity of 120, combined with an ethylene permeance of 135 gas permeation units. These advancements hold promise for improving hydrocarbon separation processes, contributing to increased efficiency in industrial applications.

3. Mechanisms and Principles of Membrane Technology

The surface chemistry, morphology, bulk structure, and production methods of membranes can all be categorized. Nevertheless, the most commonly employed membranes in the separation industries are those that exhibit asymmetry, density, or porosity.[72] In water treatment, membrane technology involves the selective passage of specific components through a membrane while preventing others from entering. This process aims to remove impurities and contaminants from the water, much like how our body's cell walls prevent the release of unwanted chemicals into the cell. In essence, membrane separation plays a crucial role in purifying water.

The driving factors for membrane separation can vary depending on the type of membrane utilized and the composition of the mixture.[73] Generally, an external force is needed to facilitate this process. To make it easier to understand, the membrane process can be classified according to the type of force used to separate the elements in wastewater. This includes a pressure difference (e.g., micro or ultra-, NF, RO), a concentration difference across the membrane, as well as a potential application in ion exchange membranes that enable ion mobility across the membrane (electrodialysis, for example).[74] Efficiency depends on the energy used, mobility, species concentration in solution or flow, etc.[7a]

3.1. Role of Membrane Structure and Properties in Separation

The membrane can be classified according to its type, structure, material membrane, and surface charge, as illustrated in **Figure 1**. Essentially, membranes can be either synthetic or natural. In addition to various membrane technologies, new

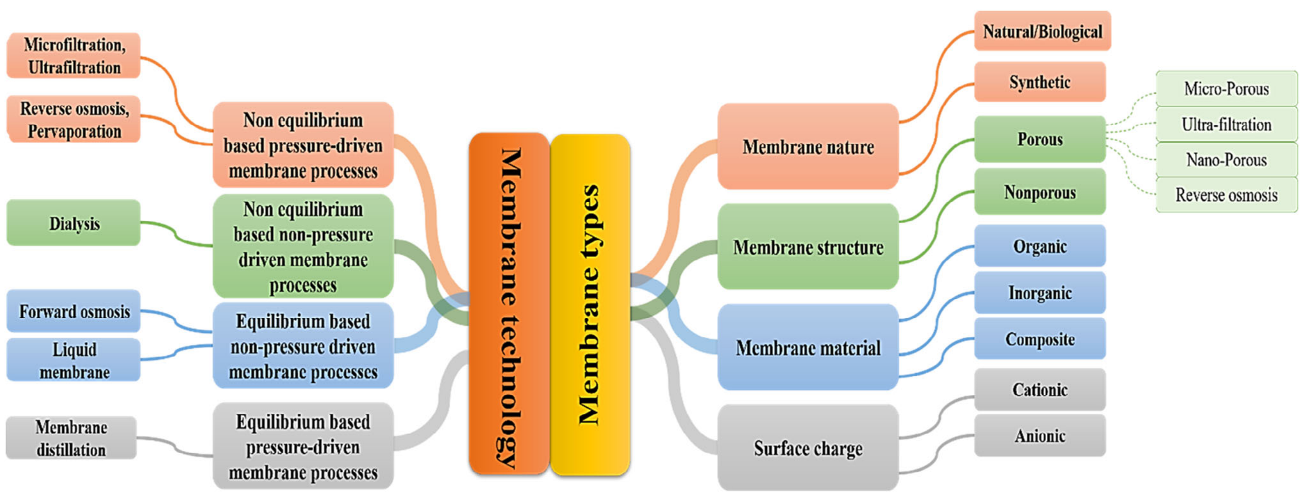

Figure 1. Schematic representation of various membranes and their processes.

approaches, such as integrated and hybrid membranes, have been developed in recent years. Municipal water treatment membranes, whether cellulosic or noncellulosic, are prepared from synthetically engineered organoleptic materials. Microfiltration and ultrafiltration membranes encompass a wide range of materials, including PV materials, polypropylene, polysulfones, polyether sulfones, and cellulose, among others. The membrane's composition is tailored based on the specific properties of these materials, such as pH sensitivity, hydrophobicity, and surface charge.

The efficiency of a membrane is primarily contingent on the characteristics of the material from which it is constructed. To attain the desired separation in a membrane-based separation process, it is essential to select a method with suitable driving forces, membrane dimensions, and thickness. The principles governing membrane separation hinge on a range of physicochemical parameters, including the Donnan effect, molecular charges, surface charges, transmembrane pressure, and crossflow velocities. Frequently, membrane separation is integrated with pretreatments involving acidity, coagulation, and physical adsorption. These pretreatments significantly extend the operational life and longevity of the membrane.[75] The process of membrane separation can be categorized into four primary groups: those relying on pressure and concentration differentials, those utilizing electrical conductivity, and those leveraging thermal conductivity.[76]

Nanocellulose membranes have garnered increasing attention among researchers for several compelling reasons, including their accessibility, cost-effectiveness, biodegradability, efficiency, and productivity. Furthermore, these membranes boast an expansive surface area, are recyclable, exhibit pH stability, and offer flexibility, permeability, hydrophilicity, and potentially robust mechanical properties.[77] Moreover, the size exclusion technique has yielded promising outcomes in retaining viruses within membranes derived from regenerated cellulose, millefeuille cellulose, and cladophora cellulose. Cellulose-based membranes can also benefit from repellence mechanisms and electrostatic interactions. Since the onset of the COVID-19 pandemic, scientists have been diligently working to develop effective membranes capable of resisting the virus. The utilization of cellulose-based membrane processes holds the potential to prevent or even mitigate the spread of severe acute respiratory syndrome and similar pathogens.[77,78] Persistent microorganisms earn their classification due to their enduring presence, toxicity, widespread distribution, and propensity for biological accumulation in ecosystems. These compounds have also been linked to various health concerns, including testicular cancer, kidney cancer, ulcerative colitis, thyroid cancer, thyroid disease, high cholesterol levels, and various carcinogenic effects on human immune function and cancer cells.[79]

3.2. Transport Mechanisms Across the Membrane

In membrane separation, chemical species are distributed through membrane interphase based on differential transport rate. This transport rate depends upon the kinetic energy of the component, its mobility, and its concentration in the interphase.[7a] The successful separation of chemical constituents relies on several key elements, including the overall molecular size of the membrane, its morphological structure, and its chemical affinity. The effectiveness of membrane-based separation processes is highly dependent on the specific types of membranes and their respective modules.[80] The size of a membrane pore is typically measured by membrane manufacturers indirectly through its molecular weight limit, which is usually expressed as the minor molecular weight component that would be retained with a minimum of 90% efficiency and is typically expressed as Daltons.[81]

The membrane separation process can be categorized and defined using various criteria. In this process, a membrane serves as a selective barrier between two phases during filtration, as shown in **Figure 2**a. Mass transport across the membrane is facilitated by a driving force, which pushes particles toward the membrane's surface. Some particles pass through the membrane, while others are retained on its surface.[82] These membrane separation techniques find application in diverse fields and can be classified based on both the driving force involved and the underlying separation mechanism. **Table 1** lists the different membrane separation methods and their applications.

The transport of solute molecules across a membrane primarily hinges on two key factors: their solubility in the membrane and their ability to diffuse through it, as elucidated by the solution diffusion theory. The interactions between solutes and membranes, including phenomena such as size exclusion and electrostatic repulsion (as illustrated in Figure 2b), play a pivotal role in governing the solution diffusion process.[83] The topic of membrane-specific rejection of compounds is critical, as it is contingent upon various physicochemical variables. It is paramount to map and report the efficiencies of multiple membranes and membrane systems. This allows for successfully integrating two or more membrane types or strategies that would otherwise be ineffective for treating urban wastewater, thus significantly enhancing their synergy. Additionally, it would enable the development of highly efficient frameworks to treat wastewater directly on the site in various modern and agricultural areas, or, for example, wastewater from pharmaceuticals, both on an extensive and limited scale. Preventing relatively concentrated wastewater streams from diluting with other wastewater to the union water and wastewater treatment plant must be seen as a significant challenge.[84]

3.3. Factors Affecting Membrane Performance

The parameters influencing membrane performance and quality during pressure-driven membrane applications to wastewater have not been extensively discussed in most scientific publications. Factors such as the type and material of the membrane, the number of pores, the type of feedwater treatment, the pretreatment method, and the techniques for fouling control can all significantly impact the quality and efficacy of the membrane permeate as well as the overall performance of the membranes.[85] Operational variables such as feed rate and temperature, membrane properties, and feed water properties (pH and ingredient composition) may have a significant impact on membrane distillation efficiency.[86] Feed operating temperature and permeate temperature are of paramount importance in the

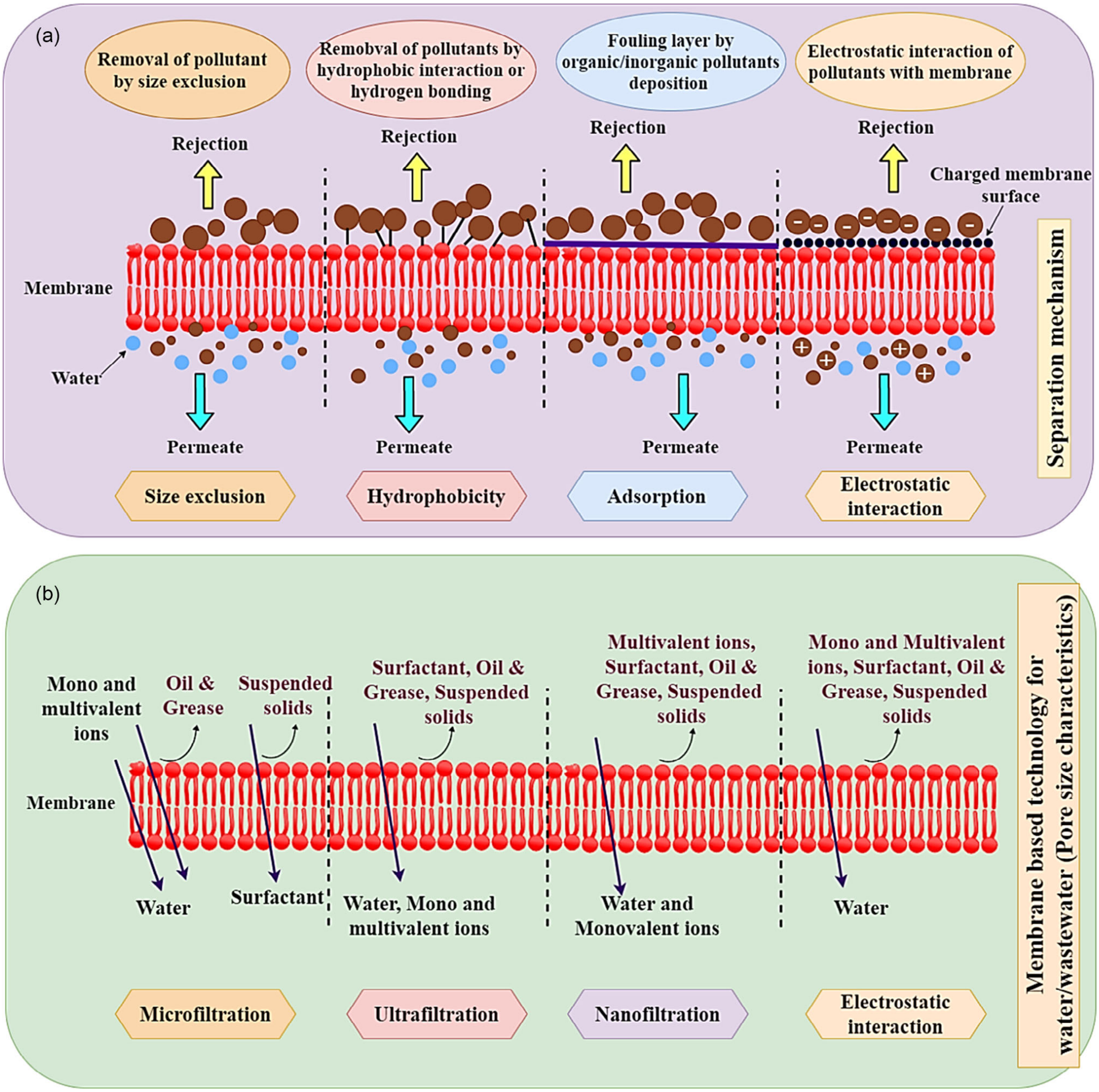

Figure 2. a) Membrane filtration and its separation mechanism; b) membrane-based technologies employing pore size characteristics. Modified from ref. [235].

membrane distillation operation, as the variations in vapor pressure due to temperature variations are the primary cause of the membrane distillation operation.[87] However, fouling is unavoidable at a more significant temperature difference.

Apart from obstructing the pores of the film, it has the potential to decrease the hydrophobicity of the layer, resulting in undesirable wetting behaviors.[88] While it is feasible to enhance the driving force to achieve a higher forward osmosis permeate flux, this increase is accompanied by a substantial rise in fouling.[89] In the presence of higher driving forces, the concentration polarization increases, resulting in a thick fouling layer forming on the forward osmosis membrane. This is due to the rise in instability encountered along the membrane. Osmotic forcing increases the concentration polarization phenomenon, thus causing the formation of a thick fouling layer.[30] The performance of direct electrical-driven processes can be affected by specific membrane properties, including the composition and arrangement of the modules and operating conditions, such as flow rate, electrical current, and temperature.[90] With an increase in current density, there is a corresponding rise in electric voltage, leading to an accelerated rate of ion movement and, consequently, an enhancement in water efficiency.[91] In such a

Table 1. Membrane separation techniques and their applications.

Membrane separation technique		Membrane type	Membrane pore size [nm]	Driving force	Mechanism	Applications	References
Pressure-driven membrane separation technique	Microfiltration	Symmetric and asymmetric microporous membrane	100–10 000	Pressure difference (0.1–2 bar)	Sieving	Industries like pharmaceutical, food, and water treatment for drinking purposes. Pretreatment of NF and RO	[236]
	Ultrafiltration	Asymmetric microporous membrane	10–100	Pressure difference (1–10 bar)	Sieving	Industries like dairy, food, pharmaceutical, textile, and water treatment. Pretreatment of NF and RO	[237]
	NF	–	0.1–10	Pressure difference (10–25 bar)	Solution diffusion	Treatment of wastewater and brackish water desalination, chroma removal	[238]
	RO	–	<2	Pressure difference (15–80 bar)	Solution diffusion	Concentration of juice and milk, seawater desalination, boiler water supply	[239]
Concentration-driven membrane separation technique	Pervaporation	Asymmetric nonporous membrane	<1	Vapor pressure difference/ concentration difference (0.001–1 bar)	Solution diffusion	Separation of liquid mixture, hydrogen and helium recovery	[240]
	Gas separation	Porous/nonporous membrane	<1000	Concentration difference	Knudsen flow (porous membranes). Diffusion (nonporous membranes)	Removal of organic matter during water treatment	[241]
Electrical-driven membrane separation technique	Electrodialysis	Cation and anion exchange nonporous membrane	–	Electric potential difference	Donnan exclusion (selective transport of ions)	Desalination and separation of amino acids	[242]
Temperature-driven membrane separation technique	Membrane distillation	Microporous membrane	0.2–1 (temperature difference)	Vapor pressure difference	Vapor-liquid equilibrium	Semiconductor industry, desalination of seawater	[243]

case, reducing the membrane surface area for a particular installation size may be necessary, thus reducing the capital expenditure. In contrast, the lifespan of the membrane will be shortened due to the enhanced electrical resistance. **Figure 3** highlights the various factors that influence membrane performance during treatment.

4. Advantages and Limitations of Membrane Technology

4.1. Advantages of Membrane Technology

Utilizing membrane-based separation systems facilitates the selective transport of specific substances across a membrane layer, acting as a barrier dependent on the gradient between two phases. This technology boasts low energy requirements and a higher separation rate. In urban wastewater treatment plants, its adoption has resulted in an approximately 18-fold reduction in energy consumption compared to conventional methods.[92] Moreover, membrane-based processes, widely employed for nutrient recovery from municipal wastewater discharge, are recognized for their minimal volume requirements, elevated stability, uncomplicated process control, sufficient permeate flux, economical chemical consumption, superior pollutant retention, cost-effectiveness, and operational dependability.[93] This green technology has gained popularity due to its clean production, energy efficiency, low capital cost, and minimal environmental impact.[94]

The benefits of membrane separation technology extend beyond wastewater treatment. Molecular and scaling membrane separation techniques are versatile, requiring no phase modification for identification. Energy requirements remain low unless feed stream pressure is increased. This cost-effective and environmentally friendly process is employed for water softening, achieving molecular separation levels unmatched by other methods like centrifugation. The technology's advantage lies in processing large volumes and generating continuous product streams.[95]

Membrane techniques offer straightforward, cost-effective, and direct service for separating undesired components from wastewater, eliminating the need for intricate control systems. The high selectivity of membrane production exceeds the average volatility of distillation processes. Simplicity and automation reduce operator intervention, making them ideal for small-scale

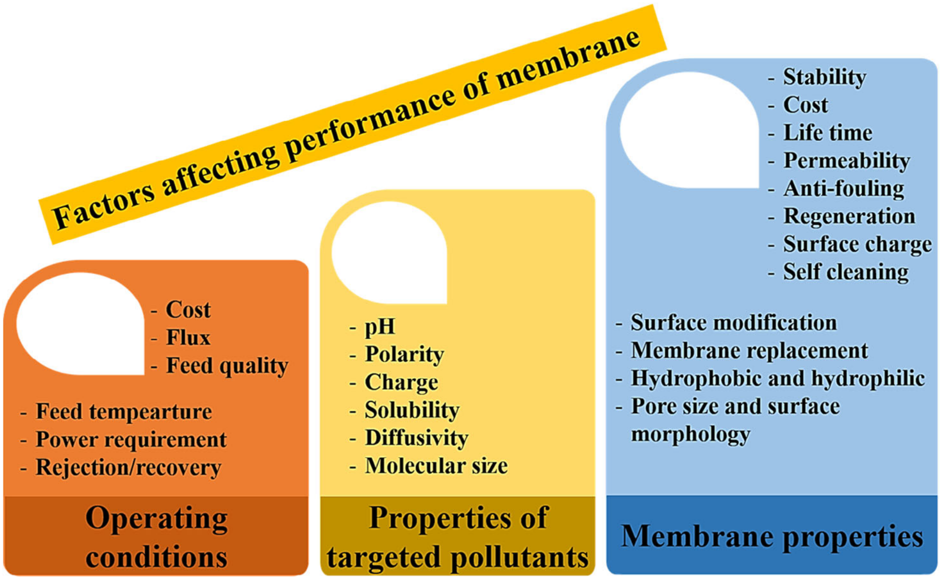

Figure 3. Factors affecting the performance of membrane during treatment.

applications. The technique effectively removes bacteria, particulate matter, and almost all contaminants' ions. With polymers and nonorganic compounds in membrane production, there is control over selectivity, and recovery of minor constituents from the source stream does not increase energy costs.[96]

In the context of circular economy benefits, membrane-based water and wastewater treatment technologies enhance resource efficiency by recovering clean water, energy, and chemicals from wastewater, as shown in **Figure 4**. They contribute to waste reduction by effectively removing contaminants and minimizing

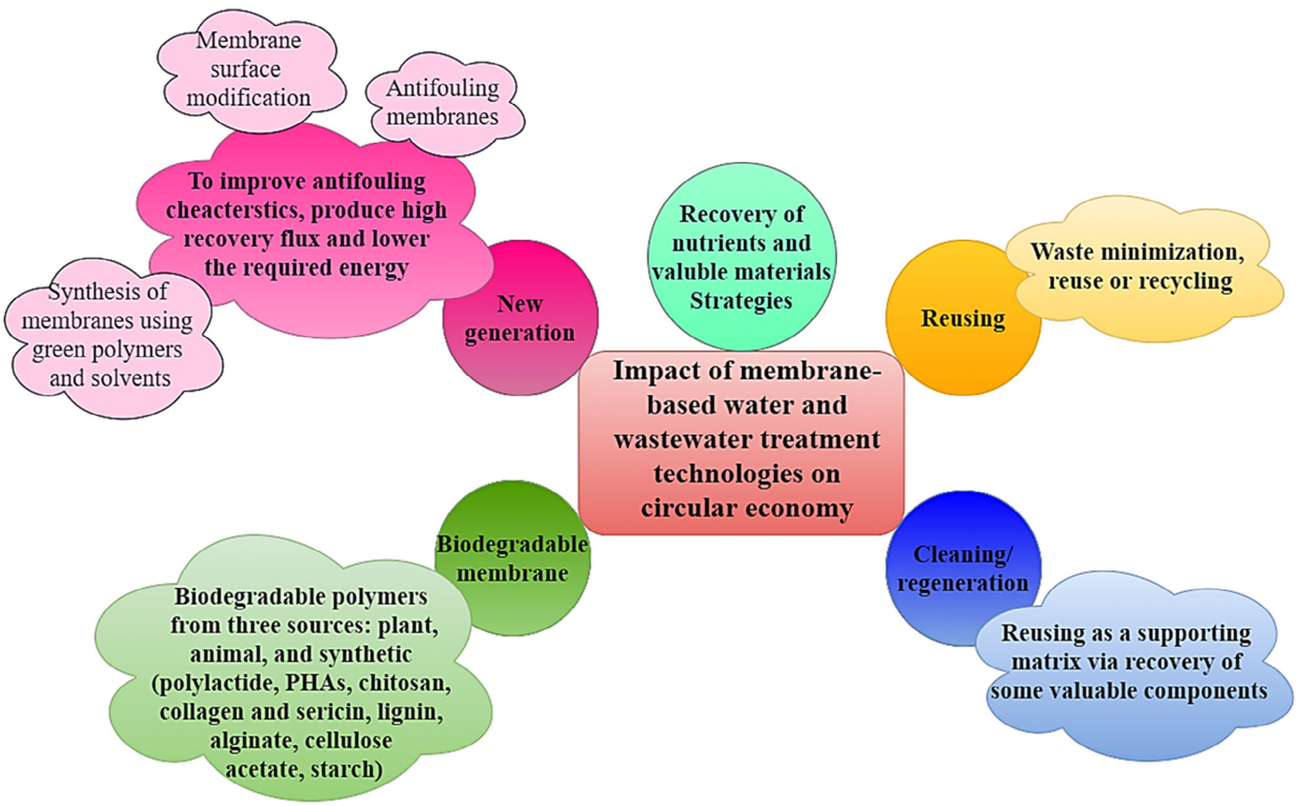

Figure 4. Membrane-based treatment technologies impact on circular economy.

hazardous waste generation. With lower energy requirements, membrane processes align with circular economy principles, leading to energy savings and reduced operational costs. Additionally, some membrane processes facilitate the recovery of valuable materials like phosphorus and metals from wastewater, reducing the need for primary raw materials. By enabling closed-loop water systems and extending membrane lifespans through proper maintenance, these technologies promote resource conservation and environmental protection, offering economic and environmental advantages to industries and municipalities.

4.2. Limitations of Membrane Technology

Various membrane technologies offer valuable applications in water treatment; however, they have certain limitations and challenges. These challenges encompass issues related to membrane modules, such as fouling, as well as other factors that can affect overall performance and efficiency in the treatment process.

4.2.1. Membrane Fouling

Traditional membrane treatment plants employ rigorous pretreatment techniques such as flotation, clotting, and sand filtration to minimize organic matter in the inlet, ensuring the protection of subsequent membrane-based units.[97] When using a selective separation membrane to transport diverse components, interactions with elevated levels of organic compounds are common, necessitating careful consideration of membrane fouling, particularly organic fouling. Fouling, characterized by the accumulation of impurities like particulates, solvents, or colloids on the membrane's edges or within its pores, results in a decline in the membrane's properties and overall performance.[98] Consequently, the membrane pores close, leading to a loss of water flow and quality. For instance, dyes or pigments in textile wastewater may aggregate to form a fouling cake layer on NF or ultrafiltration membranes. Ionic and covalent chemical connections may form, binding contaminants strongly to the membrane surface, causing an undesirable decrease in flux during membrane operation and increasing fouling extent.[99] This ultimately necessitates membrane replacement due to irreversible loss of permeance. Severe fouling requires chemical cleaning processes and membrane replacement. Fouling can be reversible or nonreversible based on the extent of surface particle adhesion. Reverse fouling can be addressed with backwashing or a high splitting force, while nonreversible fouling occurs when a solution forms an irreversible layer during filtration.[98] The term "irreversible fouling" denotes the persistence of particulate matter that physical cleaning cannot remove.

Causes and Control of Membrane Fouling: The occurrence of membrane fouling is influenced by various setup parameters, including feed characteristics (such as pH and ion strengths), membrane properties (like roughness and hydrophobicity), and processing conditions (cross-flow rates, transmembrane pressures, and temperatures).[100] Multiple factors contribute to membrane fouling, with the following key attributions: 1) Membrane material: ceramic membranes exhibit lower susceptibility to fouling compared to hydrophilic membranes, while polymeric membranes, due to their hydrophobic nature, are more prone to fouling; 2) Surface roughness: a rough membrane surface increases the likelihood of colloidal particle channeling within the membrane, elevating the risk of fouling; 3) Pore size: larger pores within the membrane heighten the chance of contamination blockage, thereby increasing the likelihood of fouling;[101] 4) Hydrophilicity/hydrophobicity: more hydrophilic membranes are less prone to fouling, while more hydrophobic membranes are more susceptible; 5) Colloidal particle interaction: colloidal particles can render the membrane negatively charged, attracting positively charged ions like Ca^{2+} and Al^{3+} from mixed liquor-suspended solids (MLSS), potentially leading to inorganic membrane fouling;[102] 6) Operation mode: filtering in cross-flow mode minimizes cake layer formation, reducing the risk of membrane fouling. Higher aeration rates and lower temperatures contribute to decreased and increased membrane fraying rates, respectively; 7) Chemical oxygen demand (COD)/N ratio: a higher COD/N ratio in the feed results in lower membrane fraying rates, improved performance, and extended operational longevity. Reports suggest that a low COD/N ratio indicates reduced fouling, but fouling frequency increases with decreasing hydrolysis ratio;[7a] 8) Organic loading rate: increased organic loading rates lead to higher extracellular polymer production, influencing membrane fouling.[103] Smaller floc size, released extracellular polymer with increasing salinity, and high solid retention time contribute to increased fouling; 9) pH levels: a decrease in pH raises the rate of membrane fouling; 10) MLSS levels: higher MLSS is associated with increased membrane fouling, and a high extracellular polymer concentration further augments the probability of fouling; and 11) Viscosity: increased viscosity enhances the likelihood of membrane fouling.[7a]

4.2.2. Membrane Modules

Industrial membrane plants need a large area of membrane to achieve the desired separation. There are a variety of cost-effective membrane packages that can be used to provide a vast area of membrane for efficient and effective separation.[76] Various membrane module designs play a crucial role in preventing membrane fraying, especially in water and wastewater treatment processes. These designs encompass plate and frame modules, spiral wound modules, tubular modules, and hollow fiber modules. The traditional plate and frame module, although one of the earliest membrane systems, is gradually being supplanted by the more cost-effective spiral wound and hollow fiber modules. Plate and frame modules now find primary applications in low-fouling processes such as RO and ultrafiltration. In contrast, tubular modules prove particularly valuable in scenarios demanding high protection against membrane fouling, typically reserved for ultrafiltration applications. The selection of a membrane module hinges on the specific requirements and challenges posed by the treatment process.

Tubular membrane systems are composed of a single, sizable tube housing multiple smaller tubes with diameters ranging from 0.5 to 1 cm. These tubes are interconnected in series, creating a large number of parallel flow paths.[104] At the commercial scale, these systems are typically constructed with a few membrane envelopes, each covering an area of 10–20 square feet and encircling an axis collection pipe. Commercial spiral wound modules are approximately 0.66 feet wide and 3.33 feet long, with designs featuring multiple envelopes that allow the permeate to pass through a central pipe, reducing pressure drop. Hollow fiber modules, in contrast, have diameters ranging from 10 to 20 cm and heights of 3–5 feet. They are typically supplied with an external feed stream, and water penetrates the fiber luminaire within the membrane. Many fibers are bundled together and sealed at both ends with epoxy resin to form the outer shell.[105] These variations in membrane module design cater to different applications and treatment needs in water and wastewater processing.

4.2.3. High Capital and Operational Costs

The capital and operating costs associated with large-scale membrane-based water treatment systems tend to be more expensive than those associated with freshwater systems.[106] This is a major disadvantage, particularly in the case of developing countries, where per capita income is significantly lower than the international average. Beyond the additional cost, the most notable challenge associated with membrane systems is fouling.[107] The occurrence of membrane fouling in industrial membrane water treatment plants has been extensively reported.[108] The cost of operation can also rise due to the rise in transmolecular pressure needed to maintain filtration. Chemical cleaning and monitoring are often necessary to prevent membrane fouling. In particular, ultrafiltration and microfiltration systems automatically require backwashing sequences as often as two to four times per hour, which is dependent on the quality of the feed water and the flow of the filtration fluid. This is necessary to reduce the amount of fouling before the next filtration sequence.[106]

The majority of large-scale membrane water treatment facilities are equipped with computer-aided process control hardware and software, ensuring continuous operations with minimal human involvement.[109] However, regular maintenance is essential, incurring additional expenditures for system operators. While economies of scale have lowered membrane production costs, associated expenses such as labor, electricity, and spare parts have increased, posing a significant obstacle to widespread adoption, especially in developing countries.[110] A comparative analysis reveals that membrane systems, despite offering a reduced footprint advantage, entail significantly higher capital and operational costs than traditional systems.[111] This becomes particularly relevant in urban areas with high population density,[112] where land acquisition for traditional water treatment plants is costly and time-consuming. While compact membrane systems address this issue, their smaller footprint may not be the only cost-saving factor, as the capital and operating costs of larger traditional systems are comparatively lower, making them more viable in developing countries.[113]

The electricity cost is one of the primary operating costs of a large membrane water treatment system. It is estimated that the electricity consumption of an industrial water treatment system with ultrasonic membrane technology may exceed twenty times that of a conventional system using the same raw water source as feed. In recent years, polymeric membrane production costs have decreased significantly due to the development of more efficient production techniques and economies of scale and are expected to remain relatively low in the foreseeable future due to the advent of mass production and the emergence of competitive membrane manufacturers. In some developing countries, membrane-based systems are only available in privately owned factories to meet production needs, as there is a lack of clean water supply in government-owned facilities. A modern film filtration plant is expected to cost just 6% as much as a comparable traditional structure, according to research. However, the ultrafiltration treatment system is estimated to have multiple times higher power consumption.[114]

Table 2. Comparison between conventional and ultrafiltration membranes based on cost.

Membrane system	Construction cost/capital cost	Operational cost	Maintenance cost	Land requirement
Ultrafiltration membrane	Higher	Higher	Higher	Lower
Conventional sand filters	Lower	Lower	Lower	Higher

The membrane system's hidden costs include regular maintenance due to complex automation processes, necessitating highly qualified technicians and engineers, resulting in considerable expenses. The need for frequent backwash or cleaning in membrane systems, compared to traditional systems, adds to operational costs.[115] A detailed cost-based comparison in **Table 2** highlights the trade-offs between conventional and ultrafiltration membranes, revealing opportunities for cost-effective automation systems. However, a thorough assessment indicates that, despite potential advantages, ultrafiltration systems are notably more expensive overall when treating raw surface water.[114] Overall, **Table 3** lists the advantages and disadvantages of different membrane modules.

4.3. Approaches to Overcome Membrane Fouling

4.3.1. Common Approaches

Various techniques are employed to address fouling-related issues.[116] These methods encompass mechanical cleaning, which entails applying direct pressure to the membrane surface to alleviate concentration polarization and hinder fouling. Additionally, the application of shear stress to the membrane surface contributes to the reduction of turbulence, aiding in fouling prevention. The effects of air sparging on fouling can vary, depending on specific conditions and aeration rates. Moreover, ultrasonic mitigation entails the utilization of ultrasonic-assisted aqueous media to reduce concentration polarization and remove both insoluble and soluble particles from the membrane surface. The efficacy of these techniques may vary based on the specific circumstances and applications in which they are implemented.[117] Chemical cleaning incorporates acid, base, oxidant, surfactant, and chelates, along with the recent inclusion of nitrite rhamnolipids acids. These acids play a crucial role in removing foulants by solubilizing and neutralizing the bases responsible for the hydrolysis and solubilization of the foulant, ultimately leading to its saponification.

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Table 3. Membrane characteristics, advantages, and disadvantages.

Factors	Advantages	Challenges/limitations	References
Ultrafiltration	Cost-effective, simple process, and more thermal stability	Lack of complete removal of suspended solids, bacteria, and other pathogens (viruses)	[244]
Microfiltration	Low cost compared to other filtration techniques, low in pressure and energy consumption	Treated effluent displays reduced quality, heightened susceptibility to oxidants, and achieves diminished removal of suspended solids and bacteria.	[244]
RO	Easy operation, better efficiency, effective removal of mineral salts	High capital and operational costs necessitate pretreatment and elevated pressure for the treatment process	[245]
NF	Less energy for treatment, easy operation, better efficiency, high water permeability	High cost, sensitive to free chlorine	[72]
Membrane as electrode	Membrane materials are categorized based on their electrical conductivity, allowing the application of membrane technology to various processes such as electrochemical oxidation, photo electrocatalysis, eco-friendly methods, and more.	There is a deficit in the efficiency of fragile transfer in the reactor and huge energy consumption.	[246]
Forward osmosis	Water molecules can move freely due to the lack of external pressure; the separation of the solute creates pure water, and no additional pressure is required.	Forward osmosis membrane material has advanced features that control membrane fouling.	[89]
Control of fouling	Improving the mass transfer state diminishes the degree of polarization concentration linked to fouling, resulting in a 36% reduction in the decay of flux while also increasing permeate flux. Additionally, chemical cleaning proves effective in removing any deposited foulant.	Capital cost is high, presence of complex kinetic mechanisms leads to the permanent deposition of particles onto the surface and the clogging of pores.	[247]
Pervaporation	It can be utilized to separate water of different species and its various organoleptic separations, which are both energy-saving and environmentally friendly.	Operating under extreme conditions, utilization of certain membranes is limited due to the lack of availability and the higher cost of these membranes.	[248]
Pretreatment techniques	Effectively eliminates membrane foulants, providing a safeguard against substantial environmental degradation associated with the recycling of oil-mixture wastewater.	Expensive, less efficient in treating heavy metals, more energy required	[245]
Hybrid techniques	Enhanced water quality, cost-effectiveness, efficient removal of pollutants from the environment, and improved membrane efficiency are achieved by eliminating barriers.	Despite the relatively low occurrence of membrane fouling, it still results in a reduction of both the separation rate and the membrane permeate rate.	[249]
Distillation	The liquid phase can be separated from the gas phase; the material has a high degree of permeability and is highly resistant to water; no condensation of the membrane pores is observed at the end of the reaction.	A large condenser is required due to the small amount of formed vapor being dispersed in a large amount of sweep gas high cost of equipment and installation.	[250]

Antimicrobial membranes with specific physical and chemical characteristics can be used to control membrane fouling. Hydraulic membrane surfaces are highly effective at controlling various types of foulant due to the inhibition of nonspecific interactions. Posttreatment membranes with polyacrylamide or inorganic nanomaterials are also known to reduce foulant levels.[118] Cell immobilization is a process that restricts the mobility of cells by either trapping them within a polymer matrix or affixing them to a rigid support. This technique is not infallible in the removal of pathogens or large particles; however, it is a viable alternative to traditional biological treatment systems.[119] Biological mitigation is an emerging technique with a high level of effectiveness in the control of biofouling. It works by blocking the synthesis of adenosine triphosphate, which is the primary pathway by which microbial attachments and biofilms are formed. Enzymes such as proteinase K and trypsin, as well as subtilisin, which target extracelluar polymeric substances, can be used to inhibit the formation of the initial microbial attachment, rather than disrupting the formation of a biofilm. Despite its shortcomings (e.g., instability, temperature, and pH), proteinase is significantly more effective than conventional chemicals in controlling the irreversible membrane.[120]

Electrophoresis mitigation is the use of electrical methods to control membrane fouling in a MBR. Electrostatic repulsion and electric fields on charged particles are responsible for the inhibition of membrane fouling. This can be achieved either externally, through electrophoresis, or internally, through MFC systems.

4.3.2. Artificial Intelligence (AI)-Incorporated Membrane Fouling Prediction

The rapid advancement of AI provides a significant opportunity to realize this objective, as it has been extensively utilized in a variety of areas, including healthcare, intelligent cities, intelligent searching, large-scale data analysis, and pattern recognition.[121] In the context of the fourth industrial revolution and a dynamic technological landscape, the emphasis has shifted toward optimizing system performance, long-term planning, and seamlessly integrating AI into system operations.[122] AI's role in membrane processes has been a prominent and extensively debated subject among membrane engineers and researchers for the last two decades. Notable applications include AI-powered forecasts of drug molecule filtration efficiency,[123] the design and optimization of thin-film nanocomposite membranes,[124] predictions of plasticization pressure, and estimates of membrane lifespan,[125] as well as AI-driven discrimination of membrane proteins and forecasts of membrane fouling.[125] AI adoption is on the rise within the realm of membrane filter systems, where it plays a crucial role in predicting the behavior of intricate and unpredictable systems. As these systems progressively acquire the capability to autonomously self-diagnose, AI is becoming indispensable.[126] A diverse range of AI algorithms is employed in this context, including artificial neural networks (ANN), genetic algorithms (GA), particle swarm optimization (PSO), genetic programming (GP), simulated annealing (SA), fuzzy logic (FL), adaptive neuro-fuzzy (ANF), and support vector machine (SVM).[127]

Conventional mathematical modeling, relying on mathematical or empirical techniques, often involves intricate and challenging equations, particularly in the context of membrane fouling. However, these traditional models exhibit limitations in predicting membrane fouling behavior compared to AI models, mainly due to the complexity of the fouling phenomenon.[128] Conventional models tend to oversimplify membrane fouling, lacking the capacity to comprehend temporal variability in foulant-fouling interactions.

AI, with its learning capacity and ability to process intricate nonlinear datasets, provides distinct advantages over traditional mechanistic models. AI is characterized as a "black-box", relying on dataset-based learning mechanisms rather than conventional mathematical equations for predicting membrane fouling.[118] **Figure 5** illustrates the most common algorithms for AI techniques in membrane fouling prediction. In recent years, AI has been progressively integrated into membrane filter systems, enabling highly accurate predictions of permeate flow, membrane rejection, and other crucial parameters in both pilot and commercial deployments.[129] While mathematical models may suffice for forecasting membrane fouling with low input numbers, they become intricate and challenging to develop when large numbers of inputs are utilized. Most mechanistic models, created and tested in controlled settings, lack self-educating capabilities and are unsuitable for real-time monitoring on large-scale plants. To address these challenges, intelligent methods such as high-performance computational intelligence paradigms can be employed. Despite the potential, there is limited research on various AI-based techniques for predicting membrane filtration.[127]

5. Future Prospects and Challenges

5.1. Emerging Trends in Membrane Technology

Future trends in membrane technology involve advancing selectivity and hydrophilicity through the incorporation of nanomaterials, simultaneously addressing contamination reduction. Ongoing research will emphasize understanding membrane surface effects and the creation of monitoring units for predictive contamination analysis. Water channel protein-inspired membranes present opportunities for achieving high selectivity and permeability. Integrating renewable energy into membrane processes emerges as a key strategy for reducing energy consumption and promoting sustainability by minimizing the carbon footprint. Hybrid membrane processes, an emerging frontier,

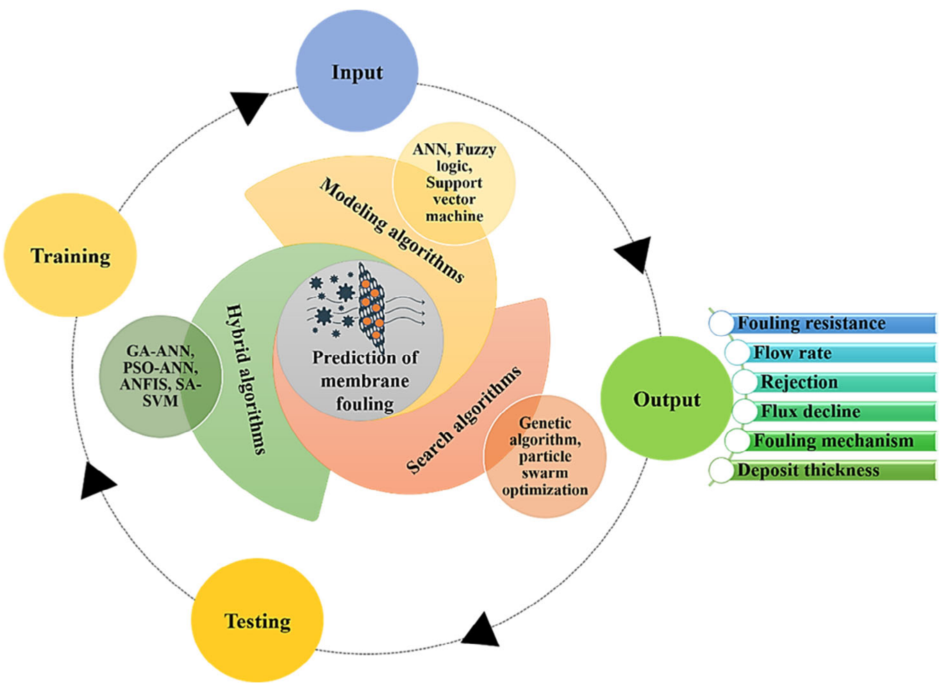

Figure 5. Algorithms for prediction of membrane fouling from training, input, and output to testing.

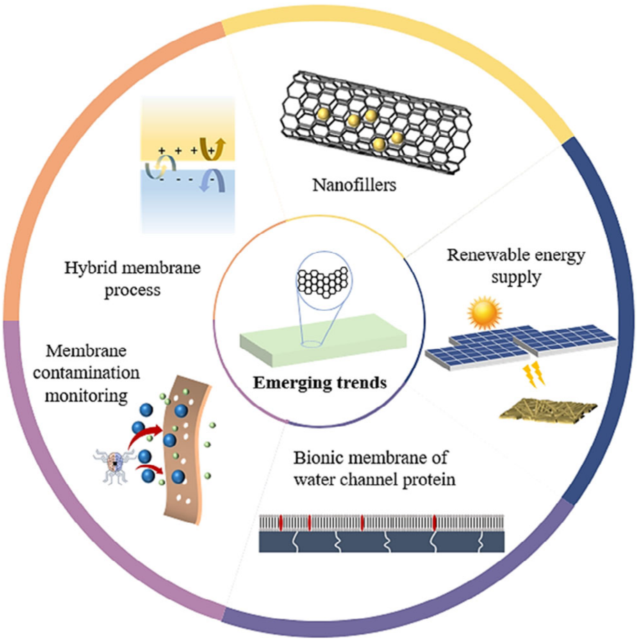

Figure 6. Overview of future trends in membrane technology development.

aim to maximize permeability and enhance commercial availability. **Figure 6** succinctly summarizes these pivotal trends in membrane technology.

Concerning RO membranes, contamination typically leads to decreased separation performance, shortened membrane lifespan, and elevated operating expenses.[130] To improve seawater RO membranes' energy efficiency and decrease associated GHG emissions, the development of higher permeability and lower permeation pressure RO membranes is crucial. The circular economy aims to reduce, reuse, and recycle waste through the interlinkages between water, food, and energy.[131] Separation through green and sustainable membranes helps reduce carbon emissions and mitigate climate change. Applying a circular economy-based approach to the utilization of agro-industrial biowastes for the production of green films will contribute to the achievement of the multiple objectives of biowaste reduction, upgrading to high-value-added products and environmental protection.[132] Membrane sustainability through value-added waste or the use of biopolymers can help reduce the consumption of natural resources and extend the service life of membranes, further supporting the circular economy's goal of maximizing resource use.

The synthesis of nanocomposite membranes using green materials as fillers is a promising research direction. Bionanoparticles are a promising material due to the inherent greenness and sustainability of the production method, as well as their good performance in reducing environmental pollutants. Kamari and Shahbazi[133] successfully developed a nanocomposite membrane using rice husk-purified SiO_2 loaded with Fe_3O_4 magnetic nanoparticles and embedded with 3-aminopropyl. This membrane demonstrated ultra-high removal efficiencies for Cu ions (93%) and methyl red dye (97%), along with excellent reusability (5 cycles: 86%). These advancements highlight the continuous evolution and diverse applications of nanocomposite membranes in membrane technology. Mondal and Purkait[134] prepared poly(vinylidene difluoride)-copolyhexafluoropropylene membranes by clove extract-mediated green synthesis of iron nanoparticles prepared and immobilized in poly(ethylene glycol) methyl ether and humic acid. The membrane has a strong catalytic nitrobenzene capacity (89.92% reduction) and can retain fluoride up to a maximum retention of 84.4%. Apple extracts can be used to synthesize silica nanoparticles, organically modified, and doped into highly porous PVDF nanofiber membranes using electrostatic spinning to effectively increase membrane efficiency and remove >99.9% of salt.[135] By using a microwave and a heat-assisted one-pot approach, Nthunya et al.[136] were able to embed apple extract into PVDF membranes and block the growth of mild and thermophilic bacteria on the membranes at the lowest inhibitory doses of 0.06–0.11 mg mL^{-1}. In addition, it has been shown that the leaves of the *Mandragora* plant were used for gas separation and ion adsorption by preparing PbO nanoparticles and synthesizing PVC nanocomposite polymer membranes through a green method, which is beneficial for increasing porosity, water absorption, and ion adsorption capacity.[137] In the future, there is a need for additional exploration into the multiobjective optimization of both nanoparticle concentration and size. This is crucial for maximizing the effectiveness of nanoparticles in catalysis, enhancing filtration efficiency, and bolstering antimicrobial activity. The utilization of materials functionalized through nanoparticle doping or deposition on their surfaces holds promise, but it also poses potential risks, as nanoparticles might be released into the environment and accumulate over extended periods. Furthermore, when designing environmentally friendly nanomembranes for industrial and commercial scale production, it is imperative to take into account considerations of sustainability, toxicity, and safety. These factors are essential for ensuring the responsible and safe deployment of green nanomembranes.

The exploration of multi-nanoparticle composite membranes holds significant promise, outshining single nanomembranes in the potential enhancement of membrane performance. The focus has intensified on developing the next generation of RO membranes, specifically through the creation of thin film nanocomposite membranes. This involves integrating nanoparticles into polyamide layers during the process of interfacial polymerization.[138] Noteworthy efforts include the development of photocatalytic membranes by Akbarzadeh and Ndungu,[139] featuring bismuth oxychloride nanocomposites with rapid electron-hole complexation rates for effective pollutant degradation. A bismuth oxychloride/silver sulfide nanocomposite membrane exhibited exceptional mechanical properties and achieved 98% desalination at 10 MPa, showcasing high-water permeability.

Using safe, nontoxic, low-cost polymers to make films can be a sustainable solution in the plastic's circular economy. To enhance selective permeation and antifouling properties, functionalized nanofillers like amine-functionalized carbon nanotubes, multiwalled carbon nanotubes, and carboxy-functionalized graphitic carbon nitride can be incorporated into the polyamide layer. This integration creates additional nanopores/channels and extends the free volume of the polyamide matrix, resulting in efficient transport pathways in the thin film nanocomposites. Polyamide membranes can be infused with nanomaterials through various methods, including sol-gel, surface metallization/mineralization, and interfacial crystallization.[140] The presence of zinc oxide and y-hydroxy iron oxide nanoparticles in the polymeric membrane allows for the overcoming of Donan repulsion, ultimately affecting the pore size.[141] The use of recycled polyethylene terephthalate reduces the production of plastic and facilitates the improvement of the hydrophilicity of the membrane surface. Khashij et al.[142] recovered environmentally friendly NF membranes made of polyethylene terephthalate to remove 94.7% of lead (II) and 63.4% of chromium (VI) from industrial wastewater, and due to the addition of zinc oxide hydrophilic enhancer, the interaction of polyethylene terephthalate nanofibers interacted with zinc oxide/y-hydroxy iron oxide nanoparticles to enhance the hydrophilic and permeability fluxes of the membranes. The interfacial polymerization method proposed by Wang et al.[143] performed ultraviolet irradiation to rearrange polyamide photo-Fries, thus optimizing the selective permeation and antifouling performance of the RO membranes. In addition, a novel biomimetic nanoparticle redox strategy was proposed by Huo et al.[144] where silver nanoparticles were reduced in situ by biomimetic nanoparticles and uniformly distributed throughout the membrane through ultrafiltration support with *m*-phenylenediamine and the bioadhesive molecule dopamine in polysulfone, thereby enhancing the water permeability of the RO membrane (42 $L\,m^{-2}\,h^{1}\,bar^{1}$) and maintained a high sodium chloride rejection rate (98.1%).

Thin composite films with nanoparticles strike a balance between gas permeability and selectivity. Enhancing antiaging and antiplasticization properties in these films requires specific modifications, such as cross-linking or annealing, without compromising the substrate structure during fabrication.[145] For biodiesel applications, oil droplet collisions may lead to agglomeration into large droplets that can be compressed onto the membrane, forming scales. This necessitates membrane cleaning to remove residual components and extend membrane life, efficiency, and repeatability.[146] In the context of developing membrane materials for biogas separation applications, the focus should shift toward improving compatibility with a broad spectrum of biogas components, prioritizing product stability over excessively high selectivity. **Table 4** outlines the performance enhancement and effects of various nanofillers on membranes.

Exploring specific chemistries of intermediate layer materials can enhance the selectivity of next-generation nanocomposite membranes against target contaminants. The lifetime and stability of nanocomposite membranes are susceptible to mechanical and chemical degradation, posing cost constraints and hindrances to large-scale synthesis and application. Achieving compatibility with renewable energy sources, considering loading concentrations, and ensuring the durability of nanocomposite membranes are crucial aspects in designing environmentally friendly nanomembranes for industrial and commercial scale production. Assessing the potential leaching of nanoparticles under various operating conditions is essential for protecting public health.[147] Advanced characterization techniques provide a better understanding of the impact of the intermediate layer on the physicochemical properties between the polymer film and nanofilm, including the interaction of the nanofiller with the polymer and the direction of transport.[148] Future efforts should focus on th surface modification of nanofillers and the optimization of the embedding process with sufficient organic and inorganic functional groups. This approach aims to improve the dispersion of nanofillers, achieving a more homogeneous distribution for enhanced performance.

The surface effect has been extensively employed in aqueous NF. In this process, the ion selectivity is determined by the electrostatic repulsion between the charged pore surface and ions.

Table 4. Effect of nanofillers on membrane separation performance.

Nanofillers	Characteristics	Membrane-separated substances	Water permeability [$L\,m^{-2}\,h^{1}\,bar^{1}$]	Effect on the membrane	Optimization direction	References
Zeolitic imidazole framework-8/carbon nanotubes	Provides an efficient and continuous diffusion path; prevents self-agglomeration of zeolitic imidazole framework-8 nanoparticles; high aspect ratio	Chlorine	–	Enhanced water permeability, high chlorine stability	Enhancement by metal-organic frame type, aspect ratio, and longevity	[251]
Octadecyltrichlorosilane-functionalized mesoporous silica nanoparticles	Hydroxy surface; hydrophilic	Molybdenum silicate; dextran	–	Significantly improved water permeability and improved dissolution stability	–	[252]
Graphitic carbon nitride/halloysite nanotubes	Hollow nanotube structure; surface hydroxyl groups; high mechanical strength; low-cost	Sodium sulfate; magnesium sulfate; magnesium chloride; sodium chloride	20	Enhanced separation properties; high water permeability	Adjustment of nanomaterial ratio and volume	[253]
Aminophenol/formaldehyde resin polymeric nanospheres	Rich in hydroxy and amino groups	Chlorine	56.3/71.3	High hydrophilicity; high reusability; strong mechanical properties	–	[254]
Cerium oxide@halloysite nanotubes	Improved surface charge; high surface area	Humic acid	206.42	Higher hydrophilicity, biofouling resistance, higher interfacial surface energy	–	[255]

To achieve the desired selectivity and solvent permeation simultaneously, it is crucial to fully utilize the pore size and pore surface.[149] Whereas the electrostatic repulsion between membranes and ions in organic solvents is sharply weakened, there is a need to develop and explore interaction forces that include hydrophobic interactions. Moreover, the use of better cross-linking agents in anion-exchange membranes and organic membranes with organic solvents for fuel cells can reduce the swelling performance of membranes while maintaining their high water absorption, yielding new membrane materials with high stability.[150] Insufficient mechanical strength of polymer membranes for biodiesel processes, ideal membrane reactors require innovative system designs with high biodiesel yields and product separation selectivity for large-scale production of fuel-grade biodiesel.[151] Nabais et al.[152] compared the effects of different MOF contents on membrane stability and gas selectivity using MMMs made of pyrrolidine-based poly(ionic liquid), ionic liquid, and MOFs for gas separation. To obtain accurate control of the structure and content of the enhanced membranes, additional investigation and optimization of working conditions will be necessary.

To further enhance the antifouling/biofouling and antimicrobial properties of membranes and maximize the utilization of pore sizes and surfaces for achieving desired selectivity and solvent permeability, ongoing efforts must focus on improving membrane surfaces' hydrophobicity and surface charge. Common methods to enhance the chemical structure of the membrane's outer layer include adding functional groups to the polymer structure, surface grafting, self-adhesion, coating, and surface treatment. Superhydrophobic modification stands out as a particularly effective approach, enhancing the membrane's self-cleaning capacity. Concurrently, surface modification techniques contribute to increased moisture permeability of the membrane. Additionally, the application of electric fields to NF systems, leveraging the Donnan effect and dielectric repulsion, allows for the manipulation of membrane surface charge. This manipulation leads to an increased membrane surface charge density, ultimately improving membrane selectivity.[153]

The accurate calculation of antifouling performance poses a challenge due to the absence of a clear quantitative relationship between functional units and antifouling effectiveness. Predicting fouling characteristics is crucial for recommending appropriate control methods to optimize system performance. To conduct a comprehensive study of parameters like pressure, misflux velocity, or specific phenomena such as surface crystallization, the experimental setup must be meticulously designed.[154] However, both optical and nonoptical analytical methods for membrane contamination lack highly sensitive techniques to identify contaminants causing irreversible contamination, as the current resolution and detection sensitivity are insufficient. There is an urgent need to develop technologies for continuous monitoring of membrane elements to quantify scale deposits and reduce the costly cleaning of membrane fouling. Lai et al.[155] employed ultrasonic time domain reflectometry to describe internal and external fouling of forward permeable membranes. This method was used to evaluate the development of the initial biomembrane, monitor the fouling layer's growth, and assess the membrane-cleaning process.[156]

Monitoring and improving RO membrane performance in reducing biofouling tendencies are ongoing. Nakaya et al.[157] utilized adenosine triphosphate as a tracer for bacterial activity to monitor biofouling in RO membranes, reflecting bacterial cell adhesion and biomembrane growth. AI models are capable of handling nonlinear issues, and hybrid models that combine mathematics and AI models may be built for membrane fouling prediction. Deep learning and AI models have emerged as novel techniques for predicting fouling behavior in membrane filtration processes. For a better understanding of fouling behavior, a thorough examination of the fouling layer on the membrane surface determines the major fouling layer components.[158] Using data-driven models with uncertainty to provide single-point predictions for individual data observations cannot be reliably used to make operational decisions in wastewater treatment plants. Machine learning or some other high-performance model may help provide a new window to address difficult ultrafiltration problems and guide the optimization of membrane systems in pretreatment and membrane modification. Deng et al.[159] compared supervised learning for modeling the ultrafiltration membrane process by semiautomatic prediction (STL) and fully autonomous prediction (RF) based on a tree model and determined that the STL model had high prediction accuracy for short-term future data, while the MSE model loss was in the range of 0.2–0.26, demonstrating an extended service life of ultrafiltration membranes under environmentally relevant conditions. The use of membrane replacement is increasing, and the manufacturing of membrane modules poses a growing solid waste problem as well as the possibility of losing important resources. These factors highlight the need for environmentally friendly disposal techniques that are compliant with global sustainability and sustainable development principles. Therefore, avoiding end-of-life membranes being considered as waste and disposed of directly in landfills can effectively enhance the circular economy of membranes. Chen et al.[160] developed a new closed-loop membrane use model using upcycled low-pressure membranes and downcycled high-pressure membranes to avoid the production and disposal of new membranes, which can reduce environmental impacts by 22–27% and enhance economic benefits by 27.1%. Tian et al.[161] introduced a novel green solvent regeneration technique that allowed end-of-life ultrafiltration membranes to regain their 100% water permeability and humic acid retention capacity after solvent treatment with methyl 5-(dimethylamino)-2-methyl-5-oxovalerate. By guaranteeing the biodegradability of solvent-water mixtures, green solvents minimize or replace hazardous organic solvents, greatly lessen the repreparation technology's detrimental environmental effects, and increase the compatibility of currently used industrial membrane manufacturing processes.

To address water channel protein inactivation and poor selectivity, new concepts for the design of highly selective and permeable water treatment bionic membranes are presented by water channel protein-based bionic membranes with specific pore shapes. The optimal bionic water channels should have a high-affinity outer surface that is suitable for the lipid membrane environment, a channel shape that is simple to construct during preparation and offers effective water transport.[162] Water channel proteins control the wettability of protein channels by regulating the conformation of certain amino acids in the channels.[163] The ultrashort, high-affinity carbon nanotube channel developed by Liu et al.[164] is a biomimetic water channel with high permeability ($1936 \pm 123\ \mu m\ s^{-1}$) and ion selectivity (complete rejection of salt ions), and thus assembled into a tubular structure to facilitate water conduction. Hence, the development of advanced functional bionic materials holds significant importance in ensuring the effectiveness of permeable bionic water channels. Simplified engineering of hydrophilic bionic surfaces stands to greatly streamline the membrane-based remediation of water environments, fostering the swift advancement of fields heavily reliant on surface properties. This includes applications such as controlled release mechanisms and anticorrosive coatings. The hydrophilization process, which creates a hydraulic layer, proves effective in preventing contaminants from reaching the membrane, presenting a viable solution for mitigating contamination in forward osmosis membranes. Li et al.[165] designed and produced a tannic acid-taurine layer by surface separation modified with dopamine and polyethyleneimine, which effectively improved the hydrophilicity and stain resistance of the substrate. The deposited eco-friendly bionic coating greatly enhanced the hydrophilicity and permeability of the membrane, and Yang et al.[166] performed aqueous remediation by one-step codeposition of dopamine and tannic acid on a hydrophobic polyvinylidene fluoride membrane to achieve efficient separation performance and antifouling potential. The water channel protein layer contains a lipid bilayer that provides rapid water permeability and efficient removal of salt ions and contaminants. Chen et al.[167] used a mixture of laccase and carbon nanotubes to produce a biomimetic dynamic membrane with a loose biomimetic layer with high filtration resistance to improve catalytic efficiency, which demonstrated excellent dye removal (>90%) and strong fouling resistance.

Utilizing renewable energy presents an appealing solution to diminish the carbon footprint of RO plants, concurrently reducing GHG emissions and operational costs. This approach severs the connection between water prices and fuel costs. Renewable energy-driven RO desalination systems are widely recognized for their enhanced reliability and sustainability compared to alternative systems. Incorporating solar power in the preheating of feedwater for RO desalination systems has been identified as a strategy to enhance overall plant performance. In remote areas, the direct integration of renewable energy with NF/RO membrane desalination technology, without the need for energy storage, is anticipated to bolster system robustness, simplicity, and efficiency while providing cost savings by minimizing reliance on expensive infrastructure.[168] For example, Zein et al.[169] used solar PV power matched to an RO plant and obtained a 37–55% cost benefit. To increase the thermal efficiency of solar power generation and subsequently maximize the productivity of freshwater, Monjezi et al.[170] proposed a new method of coupling solar PV thermal cells to RO desalination applied at Alexandria Port, Egypt. The cell unit ensured a consistent freshwater supply, effectively minimizing membrane contamination. Notably, RO membranes characterized by higher water viscosities and permeabilities exhibit an energy savings of $0.12\ kW\ h\ m^{-3}$. Introducing membrane separation coupled with autonomous PV-driven catalysis for water filtration represents an environmentally friendly and sustainable technological approach.[171] Regulation mechanisms applied to large power-rated fuel cell systems are important, and the integration of efficient energy storage systems can maintain the consistency of the power system.[172] The permeate flow of modified membranes, which display remarkable performance stability, can be improved by increased light intensity. RO membranes for renewable desalination are more expensive due to the comparatively high cost of PV solar energy and the short operation duration. RO membrane facilities may be successfully and cleanly powered by wind energy because of their cheap operating costs and great efficiency. Due to the quick fluctuations in the amount of wind energy available at each location, desalination facilities using wind energy must be adaptable enough to withstand frequent shutdown and start-up operations. A complete optimization of both technologies in terms of water and energy output is necessary for the installation of desalination systems powered by membrane-based energy systems.

The expanding reach of membrane-based processes is poised to significantly contribute to the rational design and synthesis of optimal materials, showcasing exceptional separation performance through distinct separation mechanisms. The strategic integration of electrochemical advanced oxidation processes with membrane technology emerges as an effective solution to mitigate membrane contamination issues, thereby enhancing the overall separation performance.[173] To address pH and catalyst efflux limitations, the development of new nonhomogeneous catalysts with a broadly applicable pH range is imperative. Seo et al.[174] introduced a hybrid FO-RO process that effectively reduces applied pressure, consequently minimizing RO energy consumption. Additionally, pressure-delayed permeate technology, integrated into regenerative salinity gradient energy harvesting with forward permeate hybrid systems,[175] sustains power generation, contributing to reduced energy consumption in membrane treatment processes.

In a hybrid membrane adsorption system, the combination of the mesoporous material adsorbent MCM-41 with an ultrafiltration membrane enhances the separation performance for methyl green dye removal. This system proves successful in purifying polluted water by effectively removing dyes.[176] The versatility of ionic liquids is harnessed for designing gas separation membranes, utilizing a variety of cation and anion combinations, showcasing high commercial availability.[177] However, optimization of the stability of ionic liquid membranes and their interactions with solid phases and polymers remains a crucial area for further development.

Insight into the structural and property relationships between homogeneous and heterogeneous blend membranes is essential for polymer blend matrix membranes. This understanding, predicted through transport models like molecular dynamics simulations, aids in the proper selection of polymers and compositions to enhance gas separation and permeate vaporization performance.[178] In fuel cells, the effectiveness of ionic liquids is heightened when functionalized with aerobic group fillers for membrane modification. Exploring new materials, modifying cationic functional groups, and incorporating conductive additives are avenues for improving the electrical conductivity of hydroxide in fuel cell membranes.[150]

Different hybrid formulations, such as polymer/polymer, hydrophobic/hydrophilic materials, organic/inorganic, and polymer/organic-inorganic additives/cellulose, can be developed for higher performance in fuel cells.[179] Khairuddin et al.[180] innovatively developed polyethersulfone/multiwalled carbon nanotube-1/lithium bromide-5 heterogeneous membranes through a thermally induced phase separation process. These membranes exhibit high porosity and hydrophilicity, contributing to significant algal permeation and antifouling properties. In algal culture systems, Zheng et al.[181] achieved 100% carbon dioxide transfer utilization efficiency using a multimembrane carbonated carbon dioxide transfer system, eliminating energy consumption for gas compression and transport, and reducing energy loss during capturing solvent regeneration.

In conclusion, addressing challenges related to membrane contamination and enhancing membrane performance necessitates a strategic focus on future research directions. The integration of nanomaterials with membranes emerges as a promising avenue to enhance membrane water permeability and antifouling properties. Further investigations should explore membrane surface effects, particularly delving into the interaction forces between membranes and ions. The development of a monitoring system for membrane contamination is crucial for the effective prevention, control, and localization of contamination incidents. Additionally, incorporating renewable energy sources alleviates the energy burden associated with membrane separation, contributing to overall efficiency improvement. The evolving landscape of hybrid membrane processes represents a significant trend, leveraging the synergies of complementary membrane structures to enhance selectivity and resist pollution effectively. These research directions collectively pave the way for advancements in membrane technology, addressing critical issues and fostering sustainable solutions.

5.2. Future Applications of Membrane Technology

5.2.1. Medical Sectors

Membrane technology can be used in a wide range of applications in the medical pharmaceutical industry. Oxygenated membranes are sites that simulate direct contact between alveoli and blood and gas exchange. In membrane oxygenators and at the heart of membrane artificial lung technology, the characteristics and chemical composition of the materials that comprise the membranes are crucial.[182] With the potential to be employed in blood reservoirs, tubing, and artificial blood vessels, various hydrophilic coatings on the surface of biomedical gas exchange membranes for blood oxygenation can be used to enhance hemocompatibility by lowering protein adhesion. Yi et al.[183] used porous membranes sprayed with porous fluoropolymers that exhibited excellent fouling resistance and competitive blood oxygenation performance, even after more than 12 h of continuous blood oxygenation and 2 weeks of resting blood exposure tests without degrading blood oxygenation performance. The prolonged use of pharmacologic anticoagulation to avoid circuit thrombosis can lead to bleeding issues that impede the long-term cycling of extracorporeal membrane pulmonary oxygenation.[184] The development of artificial lung membranes requires surface hydrophilic modifications effectively reducing protein adsorption, which can improve blood oxygenation efficiency and blood compatibility by optimizing blood fluid dynamics within the module.[185] Additionally, surface modification of membrane oxygenator surfaces using polymeric materials or surface modification using anticoagulant drugs and biomimetic interfacial strategies can also be beneficial in improving blood compatibility.

Hemodialysis membranes are the most important type of membrane for biomedical applications. Hemodialysis, consisting of dialyzers and circulating blood purification systems based on hemodialysis membranes, purifies the blood by removing uremic retention products through semi-permeable membranes. Since hemodialysis membranes are in direct contact with blood, they require not only membrane selectivity and contamination resistance but also biocompatibility.[186] In this context, Zhong et al.[187] combined polyethylene glycol with polysulfone by copolymerization to enhance hydrophilicity, and the synthesized copolymers were created by nonsolvent induced phase separation to improve blood compatibility and additive leaching safety issues in ultrafiltration membranes. Optimized copolymer membranes exceeding the hemodialysis performance of conventional membranes are widely used for the treatment of chronic kidney disease. Acetate/hydroxyapatite has very good cytocompatibility and hemocompatibility, and Hayder et al.[188] used a phase conversion method to prepare composite membranes with polymeric nanofillers exhibiting good uremic toxin permeability and bisphenol A retention.

Furthermore, hemodialysis membranes have the potential to selectively capture circulating tumor cells, and Jarvas et al.[189] immobilized antihuman EpCAM antibodies on the membrane surface to facilitate enhanced capture of tumor cells. Highly biocompatible bilayer Cu-1,3,5-benzenetricarboxylic acid-modified nanofiber membranes achieved effective removal of 82.3% creatinine and 92.8% urea, and the nanomaterials exhibited high performance in removing uremic toxins through electrostatic interactions and hydrogen bonding interactions.[190] The development of FO membranes with high urea retention continues to be a research goal in FO dialysate recycling to obtain better water quality, shorter hemodialysis times, and lower costs. Hysteresis starting (HRO) membranes have been proposed as promising membranes that can be scaled up for hemodialysis to address the removal of large molecules of uremic toxins. Addressing the costs associated with the synthesis and incorporation of modifiers plays an important role in scaling up the production of hemodialysis membranes from novel materials. Optimizing membrane design methods to provide cell culture and biocompatible microenvironments that better mimic the properties of human tissues reduces rejection and inflammatory responses.

Moreover, the expansion of membrane biosensors is seen to detect changes in parameters and target proteins within the organism. Santocildes-Romero et al.[191] developed novel polymeric mucoadhesive membranes synthesized with poly(vinylpyrrolidone) and Eudragit RS10 were used for topical drug delivery for the treatment of oral mucosal lesions. Additionally, Han and Steckl[192] employed two separate core-sheath fiber membranes made of Eudragit polymers, resulting in a variety of pH responses in the physiological pH range, with uses in cutting-edge medications and sensors that target illness and harmful compounds. Furthermore, Zhang et al.[193] created fluorescent molecular blotting membranes by incorporating L-cysteine-capped manganese(II) as a biosensor. This innovative approach achieved a remarkable 93%–103% recovery rate for lysozyme detection in the blotting membranes. This breakthrough enabled the investigation of the connection between abnormal lysozyme levels and the onset of leukemia and kidney disease. MXene-based combination bionic bilayer lipid membrane biosensor can effectively detect BC biomarker BRCA1, effective electrochemical detection of tumor suppressor genes (BC mutated genes), which is beneficial to help repair damaged deoxyribonucleic acid.[194] The selectivity and sensitivity of fluorescent membranes for target proteins are superior to that of reference proteins, and membrane structures are proving promising for practical applications in medical target protein detection. An et al.[195] employed oxazine 170 perchlorate-ethylcellulose membranes to create a fluorescent biosensor that had high sensitivity, accuracy, and self-correction through the enzymatic reaction of L-arginine and L-asparagine. Scaled fluorescence biosensors with membranes for ammonia and mounted enzymes will create new possibilities for optical imaging and analytical sensing in biological and clinical chemistry processes. Independent enzyme-modified responsive polymer membrane biosensors allow for appropriate combinations of different responsive polymer membranes and enzymes (e.g., urease detection of *H. pylori* infection), with excellent selectivity for components of complex matrices, and membranes manufactured in large quantities in a cost-effective and reproducible manner enabling sustainable medical diagnostics.[196] Nanocomposite membranes made of bacterial cellulose are attractive candidates for prospective use in biosensors and tissue engineering due to their conductivity.[197] Furthermore, the development of disposable and low-cost paper biosensors for single-step detection is user-friendly and cost-effective, such as a mesoporous membrane coated with branched-chain starch for α-amylase detection,[198] which holds great promise for disease diagnosis and glucose-lowering drug screening. Micron and nanofabrication technologies greatly improve the sensitivity and specificity of biomolecule detection, and standardization of procedures will be an important step in the diffusion of membrane technology, facilitating advances in the application of environmental monitoring and clinical analysis. Stabilized lipid membrane interface in membrane biosensors provides a biocompatible environment that resists nonspecific adsorption of serum components, anions, cations and toxins, thus providing a low background signal in the assay.[199] However, novel biosensor technologies will need to be supported by building portable devices to rapidly detect toxins in the future.

Using hydrophobic and electrostatic interactions, bacteria quickly attach to the surface of biological materials, grow, and accumulate, producing multilayer cell clusters on the membrane surface. Bacterial adhesion and contamination of various substrate surfaces have raised serious concerns globally in the healthcare sector, food contamination, resulting in a serious waste of resources and an increasing medical burden.[200] High value-added proteins adsorbed to the membrane during sterilization, resulting in product loss, is a critical issue. The demand for sterilizable membranes is gradually increasing in the pharmaceutical and food industries. The double-layer photothermal paper-based composite film collects incident light and converts it into heat, opening up the use of high-temperature steam sterilization. The photothermal conversion layer, made of graphene, gains heat and evaporates, resulting in a steam temperature of 132 °C or higher, allowing for efficient sterilization within 5 min.[201] Cui et al.[202] developed superhydrophobic composite membranes featuring photodynamic antibacterial properties through electrostatic spinning. They effectively eradicated a substantial amount of *S. aureus* and *E. coli* from the membrane surface using light irradiation, achieving a completely sterile surface. This photodynamic sterilization performance of superhydrophobic electrospun laminates can be used in food packaging and storage and healthcare applications. Light-induced antimicrobial materials are at the forefront of advanced green materials, with membranes that effectively intercept pathogen particles through porous nanostructures and are biocidal when exposed to sunlight, making them suitable for bioprotection applications.[203] Membranes that have been coated with MXene have the potential to function as an antibiofouling membrane that also has antibacterial action against typical aquatic microorganisms. Titanium carbide MXene membranes were employed by Rasool et al.[204] to combat *E. coli* and *B. subtilis* with a 73% antibacterial rate and 99% bacterial growth inhibition. Additionally, endothelialization and antibacterial bifunctional electrospun membranes may be employed as potential vascular grafts.[205] The self-sterilizing membrane surface displays virucidal efficacy by generating oxidative stress to effectively destroy viruses, which offers great potential in combating COVID-19 droplet infections. The developed novel C-dot-PVDF film has strong hydrophobicity, which ensures excellent COVID-19 virus particle blockage with breathability and enables solar-induced self-sanitization based on the efficient absorption of sunlight by the embedded carbon dots and the concomitant heat dissipation.[206]

Bacterial infections can result in persistent wounds that never heal, serious tissue damage, mortality, and higher medical expenses. Due to their potential therapeutic characteristics and drug loading and release capabilities, biopolymers are increasingly being considered as materials for wound dressing. The capacity of appropriate wound dressings to prevent bacterial adhesion is another crucial quality. Hydrogel-based wound dressing films, also developed from polymers, are doped with silver nanoparticles that promote the high intensity of fibroblast and neovascular formation in tissues, thus demonstrating the stimulating effect of hydrogel membranes on wound healing.[207] To protect and soothe the wound site, flexible skin-like membranes with great water and moisture permeability are desperately needed.[208] Yue et al.[209] performed custom-designed in situ electrostatic spinning, which allows the preparation of fibrous membranes directly onto human skin. High antibacterial activity is guaranteed by this membrane material, which also boasts outstanding waterproof and breathable qualities to increase comfort and make it easier to realize applications for flexible electrical sensors and wound dressings. The behavior of skin membranes' drug release and capacity to absorb traumatic exudate is significantly influenced by their lysis characteristics. Kimna et al.[210] controlled gentamicin release from maize alcohol-soluble protein bilayers was created and was thought to be a promising biomaterial for skin tissue regeneration with good mechanical properties, nontoxic behavior, and antimicrobial activity. Chitosan-based membranes have the properties of ease of manufacture and good stability. Glycerol-toughened chitosan-containing membranes incorporating tetracycline hydrochloride and silver sulfadiazine have strong antibacterial effects against *E. coli* and *S. aureus*, respectively, providing high therapeutic efficiency to promote wound healing.[211] By using a composite membrane made from an ethanol extract of *E. schimperii* and functionalizing bacterial cellulose, Fatima et al.[212] demonstrated bactericidal properties against gram-positive *Staphylococcus* aureus, advancing the environmentally friendly, economically advantageous development of medical biomaterials. The antifouling electrospun membrane's improved healing quality and quicker wound closure kinetics demonstrate how the ideal physical structure and chemical properties combined create an environment at the membrane interface that encourages wound healing in chronic wounds. Carboxymethylcellulose-based membranes demonstrated to have excellent hemolysis and cytocompatibility with fibroblasts enhance the efficiency of the wound healing process in normal and diabetic rats, promoting wound closure and tissue regeneration.[213] Electrospun nanofibrous membranes play an important pioneering role in the drug transport system in wound healing, and optimization and improvement of the physicochemical properties of nanofibers are conducive to the promotion of controlled or multistage release of biomolecules at the wound site, thereby promoting wound healing.[214] However, finding the ideal material to develop remains a challenging issue that requires research and improvement in the properties of biomaterials that are essential in healthcare. 3-D printing allows for asymmetric membranes with high-precision 3-D structures that can be tailored to a patient's specific requirements and allows for membranes to be doped with stem cells or patient-sourced skin cells to further enhance skin regeneration and facilitate the reconstruction of the skin appendages.[215]

5.2.2. Chemical Sectors

For the petrochemical, pharmaceutical, and agrochemical sectors, separation of organic-organic solvent mixtures is crucial.[216] Membrane separation in organic solvents is still in its infancy compared to membrane separation in aqueous solutions. Organic solvents with high volatility and lipophilicity are highly toxic, and organic solvent NF membranes for simultaneous purification of organic solvents and recovery of nanoscale molecules are expected to be a sustainable technology for size exclusion molecular separation.[217] By simply applying a pressure gradient across the membrane, organic solvent NF, a relatively new technique, enables fast and long-lasting separation of molecules in the molecular weight range of 200–1000 $g\,mol^{-1}$ from organic solvents and solvent recovery. Gao et al.[217a] found that homophthaloyl chloride cross-linked modified organic solvent NF membranes were detected with high rejection rates for both remazol Brilliant Blue R (90%) and Rose Bengal (97%). According to Sukma and Çulfaz-Emecen,[218] cellulose NF membranes can achieve a maximum rejection rate of 94.0% for bromothymol blue, which means nonprotonic solvents and solutes with low affinity for cellulose are more readily rejected by cellulose membranes. The affinity of organic dyes for membranes is attributed to electrostatic and hydrogen bonding interactions. Membranes with a greater solvent tolerance are necessary for the separation of organic-organic solvent combinations. A novel nanocomposite organic solvent NF membrane with a 99% rejection of Rose Bengal and an ethanol permeability of 1.26 $L\,(m^2\,h^1\,bar^1)^{-1}$ was created by Xu et al.[219] Due to the cross-linked structure of polyimide and the special inorganic polyhedral oligomeric sesquisiloxane hybrid separation layer composite, the new nanocomposite organic solvent NF membranes also have good separation performance for a variety of dyes (such as tetrahydrofuran, dichloromethane, and dimethylformamide). The kind of organic mixture and the desired results of the separation should guide the design and preparation of the membrane materials.[5b] However, there is still an urgent necessity to broaden the scale of industrial applications to facilitate the development of organic solvent membrane applications. Conventional polymer membranes are solvent-soluble and require additional cross-linking steps, while rigid porous membrane materials with enhanced structural stability suffer from poor chemical stability, and thus membrane stability remains a key point in separating corrosive organic solvents.[220] Ultrafilms with good mechanical strength can increase the separation efficiency, permeate flux, and energy consumption and are considered a promising future trend in membrane filtration, utilizing controlled graded surface roughness to facilitate the separation of dispersed and emulsified organic solvent contaminants. As shown in **Figure 7**, the potential applications of membrane technology are outlined.

In summary, the development of membrane processes is being applied in hemodialysis, where blood can be purified to block tumor cells and toxins. Upgrading membrane biosensors

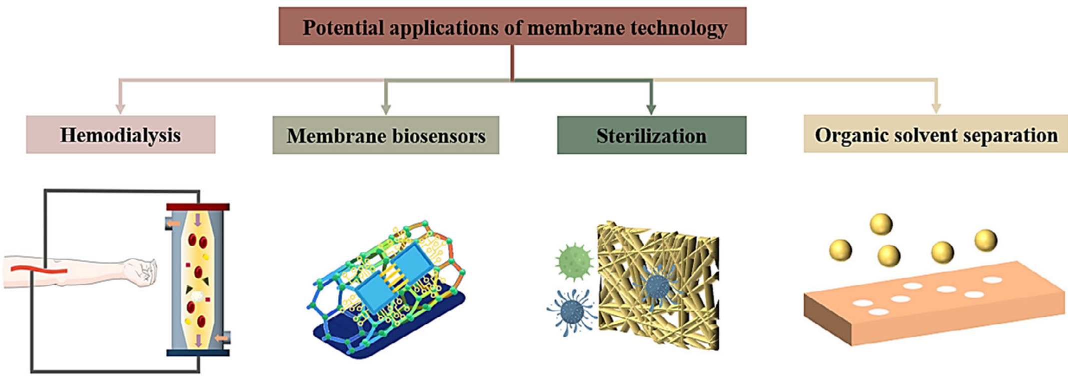

Figure 7. Potential applications of membrane technology in hemodialysis, membrane biosensors, sterilization, and organic solvent separation.

for target proteins in organisms can extend detection applications. The need for sterilization in the medical and petrochemical industries has made photodynamic and polymeric membranes promising for bioprotective sterilization and wound dressings. In addition to this, membrane separation is still in its infancy in organic solvents, and it is especially critical to develop novel membranes based on the properties of specific organic solvents.

5.3. Challenges in Scaling-up Membrane Technology

Membrane systems play a pivotal role in transferring specific information from a particular scale level to a higher scale level, catering to the specific requirements of the industrial sector. Through a pilot scale with a membrane area of $234\,m^2$, Voigt et al.[221] achieved a scale-up application of ceramic NF membranes from 0.25 to $10\,m^2\,element^{-1}$ with 100% removal of organics and 68% Ca^{2+}. Ren et al.[222] designed a flexible bifunctional evaporator with MnO_2 membrane with good light absorption, superhydrophilicity, low thermal conductivity, and excellent photothermal conversion under the full solar spectrum. The scalability of this design has been successfully demonstrated, achieving a remarkable solar-to-steam conversion efficiency of up to 81.7%. This advancement holds significant potential for power generation and solar desalination applications. In addition, Arguillarena et al.[223] successfully used a pilot-scale hollow fiber membrane contactor scaled up by a factor of 30 ($80\,m^2$ total membrane area) to recover zinc from spent pickling acid.

Despite significant laboratory research and commercialization, polymeric membranes' poor thermal and chemical resilience makes them unsuitable for use in large-scale applications. Support fluid membranes are unstable due to pressure variations across the membrane or the solubility of the organic phase in the surrounding aqueous phase.[224] Poor dispersion and low adsorption affinity of pristine carbon nanotube membranes in aqueous solutions are not available for large-scale production of organic and inorganic carbon nanotube composites.[225] Additionally, the trade-off between permeability and selectivity limits thin-film composite and standalone polymeric membranes, which perform poorly for carbon dioxide separation.[226] To attain a realistic lifespan objective of close to 3–5 years, it is thus important to create materials with improved stability, such as extremely moisture-resistant polymeric membranes.

Numerous polymers, including cellulose acetate, polysulfone, polyimide, and polyetherimide, are used as selective coatings on porous asymmetric supports in flat modules to create the majority of membranes used in large-scale industrial applications.[44] The requirement to strengthen their mechanical resistance by combining with other polymers or by integrating nanoparticles restricts the growth of bio-based membranes.[227] Moreover, composite membranes have high densities and complex manufacturing processes, requiring more sophisticated production processes and structural feature information to ensure scale-up manufacturing. The requirements for speed and drying conditions differ for each layer of the roll due to the unique material characteristics and coating procedure of multilayer laminates. New variables, such membrane vibration and electrostatic charges on the membrane surface, will need to be considered for large-scale free films. The disparities between research results obtained at laboratory size and commercial scale need the evaluation of the significance of membrane and system performance since relatively novel membrane processes currently lack dependable standards for pilot-scale setups. To bridge the gap from the lab to the pilot level, scale-up manufacturing and assessment of promising functional materials and substrate materials that preserve characteristics are actively encouraged.

Membranes must be scaled up at a reasonable cost in fields like biotechnology, where multistep separations are used to produce high-purity and valuable products. Membrane treatment plants usually require sophisticated equipment and highly automated operations as well as qualified personnel, and scaling up means higher investment costs and operations and maintenance (O&M) costs. Membrane technology relies on the pressure that delivers the permeate power, so the power bill is one of the most important parameters in determining O&M costs. Membrane performance degradation due to membrane fouling requires extensive replacement of membrane equipment, which is a valued challenge key to large-scale membrane material consumption. Large-scale use of membranes in water treatment is limited by high capital costs, and new designs of high-performance materials are always difficult to produce on a large scale at low cost.[228] The high cost of producing high-quality and reproducible carbon nanotube membranes ($1.48\,dollars\,g^{-1}$ in 2017) constrains their scale-up.[229] There are also reports of large-scale MFI-type zeolite membranes being manufactured at $2700\,dollars\,m^{-2}$.[230] This will require mass manufacturing of high-quality membranes at low prices to become a future possibility. While it is technically difficult to forecast the extent to which the market price of membranes can be further reduced, there is still a need for ongoing efforts to extend membrane lifespan, thereby reducing depreciation costs, and increasing specific flux during actual operation, resulting in cost savings. More work can be done to create functional membranes that are inexpensive, resolve the trade-off between permeability selectivity and durability, and are suitable for the intended application.

Ion exchange membranes allow the conversion of chemical substances into electrical energy, so the high energy consumption, poor selectivity, and high resistance are not conducive to industrial scale. Small molecules of $200–700\,g\,mole^{-1}$ can lead to internal membrane fouling, and Luiz et al.[231] extensively investigated membrane contamination using pilot-scale ion exchange membranes, with membrane fouling also being a major barrier limiting its scale-up. Membrane fouling may arise quickly after direct treatment of raw effluent through membranes. Fouling and high energy needs are still significant issues in nonequilibrium pressure-driven processes; hence, it is necessary to continually study effective and affordable pretreatment procedures as well as innovative fouling-resistant membranes. In addition, inorganic lithium-ion sieve membranes with high stability in the recovery of lithium, the use of powdered lithium ion sieves in column operations leads to severe pressure drop and loss of adsorbent.[232]

To enhance the specific flux in long-term operation, more sophisticated and intelligent procedures must be created. Seasonal variations in the propensity of fouling should be taken into consideration. However, the effectiveness of chemical cleaning has not been fully utilized in actual operations.

Environmental regulations will also limit the use of hazardous or nonrecyclable solvents because large-scale film production requires a lot of solvents. Large chemical usage can result in secondary pollutants and higher operating expenses, both of which can reduce membrane life.[233] The intricacy of membrane pollution requires the development of cleaners and cleaner techniques that are more effective. Based purely on the intricacy of membrane pollution, more effective cleaning solutions and cleaning procedures must be created. Effective techniques for preventing membrane contamination include routine physical and chemical cleaning, water pretreatment, and chemical addition. These techniques support long-term membrane operation.[234] Furthermore, to make the membrane process technically and financially practical for usage in wastewater treatment, effective fouling prevention techniques should be developed upstream of the membrane operation.

In summary, large-scale applications of membrane separation processes need to consider the impact of scaled-up membranes on membrane performance and lifetime in long-term contaminant treatment. And scaling up means that more and higher quality membrane materials need to be produced, and the focus needs to be on reducing membrane manufacturing costs in favor of large-scale use. Membrane contamination is a major concern in membrane separation scale-up, and cleaning fouling on membranes requires smarter systems to handle industrial scale.

6. Conclusion

Membrane technology represents a transformative paradigm in addressing pressing global challenges across various industries. Its remarkable ability to efficiently separate diverse contaminants, including organics, inorganics, pharmaceuticals, and heavy metals, has positioned it as a pivotal solution for water desalination, gas purification, and waste recycling. This comprehensive review has delved into the foundational principles, intricate mechanisms, advantages, and limitations of membrane technology, shedding light on its vital role in mitigating the looming energy crisis and fostering sustainability. Understanding the fundamental principles underpinning membrane technology is crucial for harnessing its full potential. This includes grasping membrane structure, transport mechanisms, and performance factors, all of which serve as the cornerstone for tailoring membrane systems to specific separation needs effectively. One of membrane technology's most exceptional features is its inherent energy efficiency, setting it apart from conventional separation methods. Notable examples in desalination and gas separation illustrate significant energy savings achieved through membrane-based processes. This inherent advantage not only contributes to substantial cost savings but also aligns with global sustainability goals by reducing energy-related emissions. Furthermore, the integration of renewable energy sources, such as solar and wind power, with membrane-based systems enhances sustainability and offers eco-friendly solutions to energy supply and water desalination. The adoption of green membrane technology and environmentally conscious practices further contributes to energy efficiency within the membrane landscape. Nevertheless, this review candidly acknowledges the inherent limitations of membrane technology. Foremost among these is the persistent issue of membrane fouling, which can degrade performance over time. Researchers seek innovative fouling control in large-scale applications, aiming for consistent performance. Transitioning from petroleum-based to eco-friendly membranes poses financial challenges, requiring rigorous economic comparisons for informed decisions.

The future of membrane technology promises innovation and a commitment to sustainability. As researchers address challenges such as fouling, next-generation membranes incorporating nanoparticles demonstrate improved energy efficiency. Photocatalytic membranes based on nanocomposites like bismuth oxychloride and silver sulfide hold significant promise for efficient desalination. The pursuit of safe, nontoxic, and cost-effective polymers for membrane films continues to expand the scope of applications. In various industries, from healthcare and pharmaceuticals to wound healing and chemical processes, membrane technology offers a multitude of possibilities. Oxygenated membranes facilitate gas exchange in artificial lung technology, biocompatible hemodialysis membranes enhance patient care, and membrane biosensors play a critical role in drug delivery and disease detection. However, as membrane technology scales up for large-scale applications, it faces significant challenges that require resolution for practical and cost-effective implementation. The limited resilience of polymeric membranes, especially in high-purity product separations, necessitates the development of more robust materials. Establishing reliable standards for membrane processes is essential as research transitions from the laboratory to pilot-scale setups. Moreover, addressing high capital costs associated with large-scale membrane usage, particularly in water treatment, demands cost-effective production techniques, longer membrane lifespans, and increased specific flux. Overall, membrane technology's advantages include energy efficiency, selectivity, and environmental alignment. Yet, limitations like fouling and cost-effectiveness persist. Integration with renewable energy sources, material innovation, and AI-driven optimization enhances its potential. As we navigate these challenges, membrane technology promises a sustainable, technologically advanced world.

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Conflict of Interest

The authors declare no conflict of interest.

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