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REVIEW ARTICLE

Machine learning for membrane design in energy production, gas separation, and water treatment: a review

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Abstract

Membrane filtration is a major process used in the energy, gas separation, and water treatment sectors, yet the efficiency of current membranes is limited. Here, we review the use of machine learning to improve membrane efficiency, with emphasis on reverse osmosis, nanofiltration, pervaporation, removal of pollutants, pathogens and nutrients, gas separation of carbon dioxide, oxygen and hydrogen, fuel cells, biodiesel, and biogas purification. We found that the use of machine learning brings substantial improvements in performance and efficiency, leading to specialized membranes with remarkable potential for various applications. This integration offers versatile solutions crucial for addressing global challenges in sustainable development and advancing environmental goals. Membrane gas separation techniques improve carbon capture and purification of industrial gases, aiding in the reduction of carbon dioxide emissions.

Keywords Membrane technology · Machine learning · Water treatment · Gas separation · Energy production · Sustainable solutions

Introduction

The global landscape is witnessing a seismic shift driven by two paramount imperatives: sustainable development and environmental preservation. Against a backdrop of alarming statistics, the world grapples with ever-increasing energy demands, depleting fossil fuel reserves, and the urgent need to combat climate change (Osman et al. 2023). Additionally, issues such as water and air pollution further underscored the need for a paradigm shift in how we perceive and interact with our planet. As a response to these challenges, sustainable development emerged as a concerted effort to transform the prevailing mindset (Hajian and Jangchi Kashani 2021). As a response to global warming and environmental pollution, the United Nations has developed sustainable development goals (SDGs) for the year 2030, which emphasize the urgent need for inexpensive and clean energy, comprehensive and long-term economic growth, and technological advancement as methods of battling climate change (Halawy et al. 2022; Hassan et al. 2022a, 2022b; Islam et al. 2022; Raihan et al. 2023). These objectives were established to fulfill the Paris Climate Change Agreement, reduce greenhouse gas emissions, and build a more sustainable future for the planet (SDGs 7, 8, 9, and 13) (Raihan et al. 2023).

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Notably, the International Energy Agency (IEA) forecasts a staggering 27% surge in energy demand by the year 2040, primarily driven by emerging economies and population growth. In this context, the imperative of limiting global temperature rise to within 1.5 °C above pre-industrial levels, as advocated by the Intergovernmental Panel on Climate Change (IPCC), takes on critical significance, calling for a climate emergency. The year 2030 looms as a pivotal milestone, with projections indicating that global temperatures may cross this threshold, leading to dire consequences in the form of sea-level rise, extreme weather events, and ecosystem disruptions. In response to these formidable challenges, innovative technologies have risen to prominence as indispensable tools in the pursuit of sustainable solutions. Among these technologies, membrane technology emerges as a versatile and promising solution, poised to play a pivotal role in addressing the dual imperatives of energy efficiency and sustainability (Wang et al. 2023b; Zhao et al. 2023b). Membrane technology has emerged as a versatile and promising solution for various applications, including sustainable water treatment, gas separation, and energy production, as shown in Fig. 1. As the world strives to reduce global carbon emissions from energy by 73%, the importance of membrane technology shines brighter.

The integration of machine learning has ushered in a revolutionary era for membrane design, bringing about substantial improvements in performance and efficiency. Through the power of algorithms, machine learning can scrutinize extensive datasets to forecast critical membrane properties such as selectivity and permeability, thus pinpointing materials with remarkable potential. Moreover, machine learning goes beyond mere prediction; it delves into intricate relationships within membrane structures, facilitating the development of tailored and specialized membranes for distinct

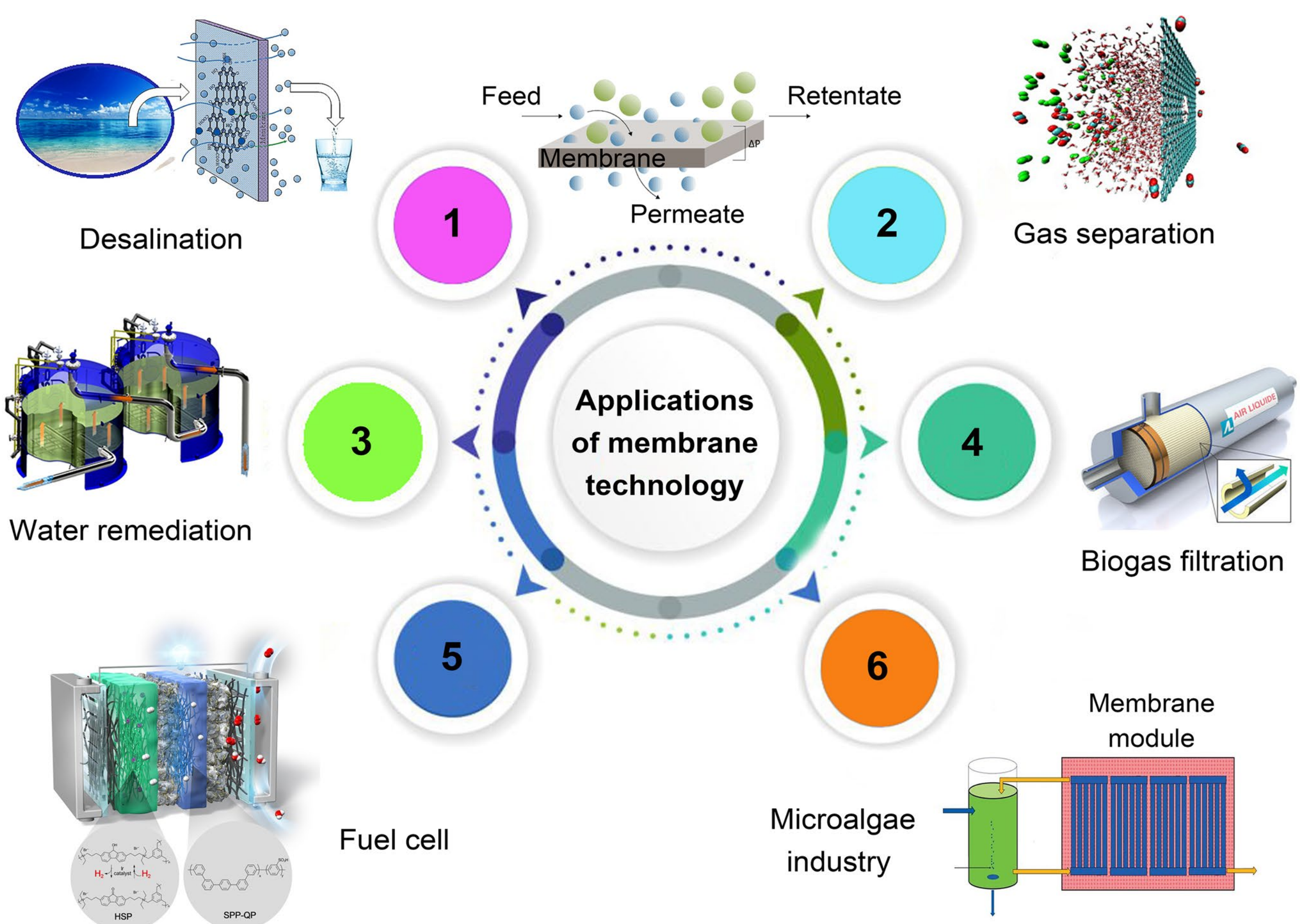

Fig. 1 Common applications of membranes. Membranes are extensively used in the desalination process, providing clean and safe drinking water from seawater sources. They are also employed in gas separation, enabling efficient carbon capture and purification of industrial gases. Membranes find application in the biogas filtration process, facilitating the purification of biogas for energy production. Furthermore, membranes are utilized in water remediation, ensuring the removal of pollutants and pathogens from contaminated water sources. In the microalgae industry, membranes are essential in microalgae biorefinery processes, enabling the extraction of valuable compounds. Lastly, membranes are integral to the energy sector, particularly in fuel cell technology, enabling efficient energy production. These diverse applications showcase the versatility and significance of membranes in various industries

applications. Notably, these machine learning models extend their influence beyond individual membranes and optimize entire systems by harnessing diverse data sources. This holistic approach results in the creation of integrated membrane systems that outperform their conventional counterparts, marking a significant advancement in membrane technology (Guan et al. 2022; Alizamir et al. 2023).

The novelty of this review is to explore and integrate the application of membrane technology enhanced by machine learning in addressing key challenges in water treatment, gas separation, and energy production. The integration of machine learning in membrane design and discovery is emphasized, as it enables the prediction of membrane properties and system optimization, leading to the development of specialized membranes for specific applications. In addition, the review aims to highlight the potential of membrane technology as a sustainable solution for clean water access, reduction of greenhouse gas emissions, and enhancement of energy production efficiency.

Machine learning for membrane design and discovery

The adoption of artificial intelligence, particularly machine learning, in numerous membrane applications has spurred significant advancements in addressing environmental engineering challenges, with a specific focus on combating membrane fouling. These recent developments have introduced modern techniques, including artificial neural networks, fuzzy logic, model trees, and genetic programming. Their implementation has yielded remarkable success on a global scale (Bagheri et al. 2019).

Machine learning, a subset of artificial intelligence, possesses the inherent capability to autonomously discern patterns by leveraging acquired data. This process of data collection empowers machines to offer appropriate responses when presented with new data arrays (Chen et al. 2020). Consequently, machine learning has earned the reputation of being a data-driven approach in the realm of designing functional materials, including polymers. Machine learning excels in predicting a diverse range of polymer characteristics, such as refractive index, glass transition temperature, and dielectric constant, by employing various meaningful descriptors with differing natures and scales. Additionally, machine learning has proven highly successful in diverse research communities, notably within the fields of chemistry and material science (Xu and Jiang 2022).

Machine learning methods find application in a wide array of tasks, including regression estimation, clustering, and classification. It is crucial to note that the choice of the appropriate machine learning method holds significant sway over the models' ability to generalize and estimate effectively. Therefore, the selection of the machine learning algorithm should be a meticulous and precise endeavor (Liu et al. 2017). Artificial neural networks, often described as black-box methods, play a pivotal role in this landscape. They establish a mapping between inputs and target outputs through a combination of biases, weights, and nonlinear and linear functions. This intricate process results in reasonably accurate predictions of values such as water flux and ion retention (Fetanat et al. 2021b). While neural network types may vary depending on the specific application, the fundamental structural principles remain consistent.

Machine learning encompasses two main categories: supervised learning and unsupervised learning, each with distinct characteristics. In unsupervised learning, only the features (represented as "x") are provided, leading to common techniques like clustering, dimensionality reduction, and pattern recognition. On the other hand, supervised learning involves providing both features ("x") and corresponding label data ("y"), facilitating the creation of mapping functions through regression or classification algorithms (Li et al. 2020). These algorithms are instrumental in achieving the design and enhancement of membrane separation processes.

The integration of machine learning in membrane design and discovery has opened new possibilities for enhancing membrane performance and efficiency, as depicted in Fig. 2. Machine learning algorithms leverage computational power and data analysis techniques to optimize various aspects of membrane technology, including materials, structures, and processes (Wang et al. 2023a). Machine learning algorithms are particularly effective in predicting and optimizing membrane properties. By analyzing large datasets of membrane materials, these models can identify patterns and correlations that are not visible through traditional methods. They can accurately predict the performance of new membrane materials, such as selectivity, permeability, and stability, enabling researchers to screen a wide range of potential materials and identify the most promising candidates for specific applications (Alizamir et al. 2023).

The improvement of membrane structures also greatly benefits from the use of machine learning methods. They can examine complex relationships between many structural factors, including the performance of membranes and their effects on pore size, surface roughness, and surface charge. With this knowledge, machine learning models may direct the creation of membranes with specialized features that satisfy certain separation needs. Researchers can boost selectivity, raise flux rates, and improve durability by modifying the membrane structure, which would increase overall efficiency. The promise of machine learning in membrane design and discovery extends beyond the optimization of individual components to the system

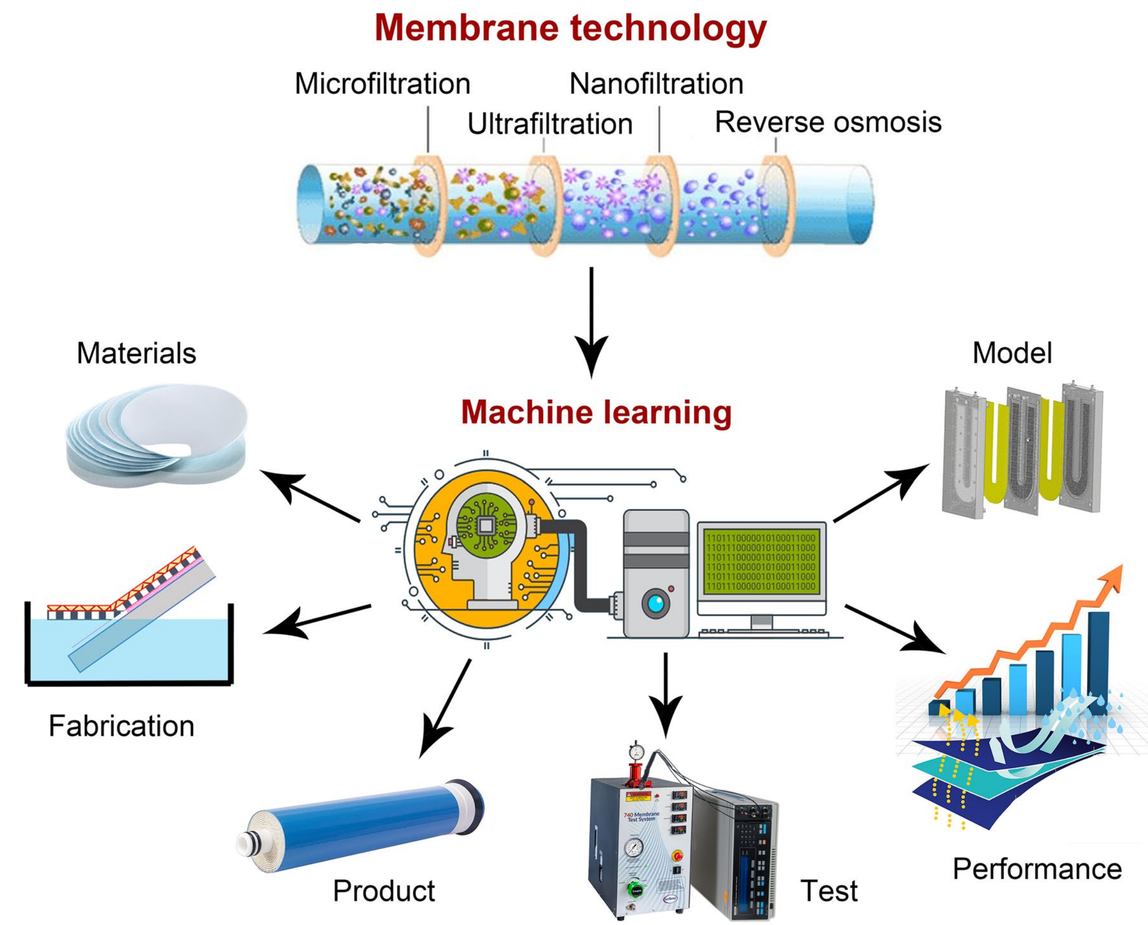

Fig. 2 Wide-ranging applications of machine learning in membrane research. Machine learning techniques are utilized for various aspects, including the optimization of membrane materials, enhancement of membrane performance, development of new membrane products, improved fabrication processes, accurate testing methodologies, and reliable predictive models. By leveraging machine learning algorithms, researchers can efficiently analyze and predict the behavior of membranes, leading to the discovery of novel materials, higher-performing membranes, and innovative fabrication techniques. Furthermore, machine learning enables the development of robust models that accurately simulate membrane behavior and predict their performance under different conditions

level. To create complete models that optimize the entire membrane system, machine learning algorithms may incorporate data from several sources, including membrane materials, process variables, and performance metrics. These models can pinpoint how various parts work together synergistically, allowing researchers to create integrated membrane systems that are more effective and perform better (Gao et al. 2022; Guan et al. 2022; Yin et al. 2022).

Artificial neural networks are applied in different membrane fabrications and separation techniques, such as reverse osmosis, nanofiltration, ultrafiltration, and microfiltration (Fetanat et al. 2021a), where perceptron and multilayer perceptron are the most utilized network structures (Yin et al. 2022). For example, artificial neural networks have been utilized for the prediction of magnesium chloride and sodium chloride rejection within the sweater by utilizing nanofiltration membranes (Darwish et al. 2007). Despite the swift growth in the development of material, the current membranes, even with high performance, do not sufficiently meet the industrial demands. Furthermore, new membranes are developed under a large trial-and-error process; additionally, the preparation and examination of membranes is money and time-consuming, which could be impossible sometimes. Machine learning can tackle such restrictions and save researchers time from wasteful rehandling work. Subsequently, researchers devote their time to more challenging issues.

Modeling plays a crucial role in achieving efficient and cost-effective process design and allows for the scaling-up of membrane systems. However, mathematical models often lack sufficient detail to accurately represent the underlying physical phenomena. They are unable to describe dynamic process behaviors and are limited to specific feeds under certain conditions. Artificial neural networks, on the other hand, are an effective predictive tool for modeling complex, nonlinear systems (Al-Zoubi et al. 2007; Madaeni et al. 2010).

In terms of membrane fabrication, Madaeni et al. (2010) focused on the modeling and optimization of membrane fabrication using artificial neural networks and genetic algorithms. A genetic algorithm (GA) performs random searches through a given set to find the best criteria of goodness, expressed as an objective or fitness function. The researchers conducted experiments on polyethersulfone (PES) and polysulfone (PS) membranes prepared by immersion participation using different solvents, non-solvents, and additives. The mechanical, chemical, and thermal properties of polymers, solvents, non-solvents, and additives were elucidated for introducing the artificial neural network. The effects of polymer and additive concentrations on membrane performance were investigated using a validated artificial neural network. The optimum concentrations to achieve maximum flux for quaternary systems (PES/polyvinylpyrrolidone (PVP)/dimethylacetamide (DMAc)/2-propanol (IPA) + water) and (PS/PVP/DMAc/IPA + water) were estimated using a genetic algorithm and assembled an artificial neural network. For the polyethersulfone membrane, a good agreement was found with experimental data and scanning electron microscopy micrographs with relative errors of 5% and 1% for flux and rejection.

In recently published research, Li et al. (2022) optimized the fabrication of membranes for wastewater treatment using novel methods by a combination of the response surface method (RSM) and artificial neural network. The aim was to develop high-performance membranes to address water pollution issues effectively. The authors proposed the integration of the response surface method and artificial neural network to optimize the conditions for electroless nickel plating (ENP) of polyvinylidene fluoride-nickel (PVDF-Ni) membranes. The response surface method was used to determine the optimal reaction temperature, reaction duration, and ammonia amount based on experimental data. The combined response surface method-artificial neural network method was then employed to predict the flux and rejection performance of the optimized membrane. The results showed that the predicted flux and rejection values of the optimized membrane closely matched the actual values, with low relative errors of 3.64% and 0.58%, respectively. Scanning electron microscopy analysis confirms the favorable microporous structure of the optimized membrane. The study highlighted the potential of using artificial intelligence techniques, specifically artificial neural networks, in optimizing membrane fabrication processes. By integrating the response surface method and artificial neural network, the proposed method offers a promising approach to enhance membrane synthesis and performance prediction. The findings contributed to the development of high-performance membranes for efficient wastewater treatment, addressing the challenges of water pollution and sustainable development.

Ritt et al. (2022) focused on the development of single-species selective membranes for high-precision separations, necessitating a fundamental understanding of molecular interactions governing solute transport. They comprehensively assessed molecular-level features influencing the separation of 18 different anions by nanoporous cellulose acetate membranes. The analysis identified the limitations of bulk solvation characteristics in explaining ion transport, as highlighted by the poor correlation between hydration energy and the measured permselectivity ($R^2 = 0.37$). Entropy-enthalpy compensation, spanning 40 kilojoules per mole, led to a free-energy barrier (ΔG) variation of only about 8 kilojoules per mole across all anions. The study applied machine learning to elucidate descriptors for energetic barriers from a set of 126 collected features. Notably, electrostatic features accounted for 75% of the overall features used to describe ΔG despite the relatively uncharged state of cellulose acetate. This work presented an approach for studying ion transport across nanoporous membranes that could enable the design of ion-selective membranes.

Artificial intelligence, as a comprehensive concept, encompasses big data, machine learning, representation learning, expert systems, and computer vision. Algorithms play a vital role in executing the operations within artificial intelligence techniques (Zhang and Lu 2021). The algorithms utilized in artificial intelligence techniques include artificial neural networks, fuzzy logic, support vector machines, genetic programming, and search algorithms (Zhong et al. 2021). Optimization approaches like genetic algorithms and particle swarm optimization are key components of search algorithms. These optimization techniques enhance the performance of modeling methods and guide the optimization of operational conditions in membrane separation processes. In addition, search algorithms can be combined with other modeling algorithms, such as artificial neural networks, fuzzy logic, and support vector machines. The integration of these hybrid algorithms often leads to improved performance due to the distinct advantages provided by different search algorithms (Niu et al. 2022). The ability to precisely predict membrane separation performance offers significant advantages, primarily in terms of efficiency and cost-effectiveness (Boyd et al. 2019). In practice, membrane performance at the pilot scale often falls short of what is predicted by theoretical models (Zhu et al. 2020). This is where machine learning plays a pivotal role in the fields of chemistry and material science.

Artificial neural networks and their variations have been applied in numerous research endeavors to predict both membrane separation performance and fouling tendencies. The majority of studies utilizing artificial neural networks for membrane fouling prediction have consistently achieved a high level of accuracy over the last two decades (Kamali et al. 2021; Niu et al. 2022). In terms of membrane fouling, (Choi et al. 2017) conducted a study to investigate the fouling characteristics of colloidal silica in a direct-contact membrane distillation system. They also explored the use of mathematical models and an artificial neural network to predict the fouling rate. The research findings revealed that the concentration of silica, sodium chloride, and the feed temperature influenced the flux in the membrane distillation system. Among the models tested, the cake formation model provided the most accurate description of colloidal silica fouling under the experimental conditions, with R^2 values ranging from 0.93 to 0.99. This suggests that the primary factor contributing to colloidal silica fouling is the formation of a cake layer on the membrane surface. Furthermore, the results obtained from the artificial neural network model demonstrated a strong correlation ($R^2 = 0.99$) between the predicted and experimentally measured output variables, confirming the artificial neural network model's capability to accurately predict the rate of silica fouling in a membrane distillation system.

Mittal et al. (2021) studied the use of artificial neural networks in modeling the vacuum membrane distillation process. The researchers used MATLAB's Deep Learning Toolbox to develop an artificial neural network to analyze the effects of operating parameters on membrane fouling. The artificial neural network was optimized to achieve a minimum mean square error of 0.58 with ten nodes in the hidden layer. The model predictions were validated with a correlation coefficient of more than 0.98. The trained artificial neural network was then used to analyze the effects of operating conditions on flux and membrane fouling. High membrane fouling was observed at high feed temperature and vacuum tightness, while higher feed solute concentrations were also responsible for high fouling. The optimization study found that high feed temperature and moderate to high vacuum tightness for lower solute concentrations and high feed temperature and low to moderate vacuum tightness for higher solute concentrations were the optimum operating conditions to achieve maximum fluxes. This study contributes to the understanding of the effects of operating parameters on membrane fouling in vacuum membrane distillation processes.

Roehl et al. (2018) focused on modeling fouling in a large reverse osmosis system using artificial neural networks. The study utilized a six-year process database containing 59 hydraulic and water quality parameters, representing 190 runs between membrane cleanings. The fouling process was divided into two phases: phase 1 involved initial particle deposition, while phase 2 included gradual biofilm and scale growth. The artificial neural network models developed for each phase identified key predictors of fouling. For phase 1, the best predictors were total chlorine, electrical conductance, total dissolved solids, ammonia, and cartridge filter pressure drop. Phase 2 fouling was best predicted by turbidity, nitrate, organic nitrogen, nitrite, and total chlorine. These findings aligned with known fouling mechanisms in each phase. The study also demonstrated the use of the fouling indicator P_{foul}, calculated from reverse osmosis system pressures, to reduce fouling rates by simulating different chlorine concentrations. The artificial neural network modeling approach proved valuable in understanding and predicting fouling mechanisms in the full-scale reverse osmosis system. This research provided insights into the factors influencing fouling in a large reverse osmosis system and highlighted the potential of artificial neural network models for monitoring and controlling membrane fouling in real-time. The use of a comprehensive, multi-year process database enabled the consideration of seasonal and year-to-year process variability, enhancing the accuracy of the models. The findings contribute to the ongoing efforts to mitigate fouling and improve the efficiency and performance of reverse osmosis systems in water treatment and desalination applications.

Park et al. (2019) developed a deep neural network (DNN) model for accurately predicting organic fouling growth and flux decline in nanofiltration and reverse osmosis membrane filtration systems. The study utilized high-resolution fouling layer images obtained from optical coherence tomography (OCT) as input data for training the deep neural network model. Compared to existing mathematical models, the deep neural network model demonstrated superior predictive performance. It achieved an R^2 value of 0.99 and a low root mean square error (RMSE) of 2.82 µm for fouling growth simulation and an R^2 value of 0.99 and RMSE of 0.30 $L.m^{-2}.h^{-1}$for flux decline simulation. These results indicate that the deep neural network model accurately simulated the complex behaviors of membrane fouling. The use of optical coherence tomography as a fouling monitoring device provided fine-scale data on the membrane surface, allowing real-time observation of fouling. However, optical coherence tomography has limitations in continuous monitoring and predicting future fouling behavior. The deep neural network model addressed these limitations by providing predictive information based on the obtained images. Overall, the study demonstrated that the data-driven approach using deep neural networks, specifically the advanced version known as deep neural networks, is a promising alternative for modeling membrane fouling and flux decline in high-pressure filtration systems. By leveraging large amounts of image data, the deep neural network model achieved higher predictive accuracy and can contribute to optimizing the operation of water treatment processes.

Shim et al. (2021) focused on the development of a deep learning model using long short-term memory (LSTM) to simulate the influence of natural organic matter (NOM) on nanofiltration systems. The goal is to predict variations in filtration performance and fouling growth, which are crucial for controlling membrane fouling in water treatment processes. To train the long short-term memory model, lab-scale membrane fouling experiments were conducted using four types of natural organic matter: humic acid, bovine-serum-albumin, sodium alginate, and tannic acid. Real-time 2D images of the cake layer formed on the membrane were obtained using optical coherence tomography (OCT). The experimental data, including permeate flux and fouling layer thickness, were used as input variables to train the long short-term memory model. The results showed that the long short-term memory model performed well in predicting permeate flux and fouling layer thickness, with root mean square errors of less than 1 $L.m^{-2}.h^{-1}$ and 10 µm, respectively, during both the training and validation steps. This demonstrates the capability of deep learning to simulate the influence of natural organic matter on nanofiltration systems and potentially other membrane processes. The research highlights the advantages of data-driven models, particularly deep learning, in predicting fouling behavior without relying on complex mathematical equations. The long short-term memory model's ability to analyze sequential events and consider temporal variations contributes to its improved prediction performance. However, further exploration and application of the developed model in industrial settings are needed to bridge the gap between experimental and modeling approaches in membrane research.

The study conducted by Niu et al. (2022) systematically reviewed the application of artificial intelligence techniques in predicting membrane fouling in the last 20 years. Various artificial intelligence algorithms, including artificial neural networks, search algorithms, fuzzy logic, genetic programming, and support vector machines, have been successfully used to predict membrane fouling in a variety of membrane-based processes. Over the past 20 years, artificial neural networks have emerged as the dominant algorithm for predicting membrane fouling in various membrane filtration systems. The working principle of artificial neural networks is flexible, allowing for the adjustment of the number of neurons in the input and output layers based on the variables involved. Due to its simplicity and accuracy, multilayer perceptron neural networks are widely used to simulate membrane fouling processes. It is noteworthy that radial basis function neural networks, characterized by a simple topology and faster computation speed, are more suitable for real-time prediction. A convolutional neural network algorithm, using fouling images as input variables, can be used to predict the thickness, porosity, roughness, and density of the fouling layer and to visualize the evolution of the fouling layer. So far, the application of artificial intelligence-based models to membrane fouling in forward osmosis and membrane distillation is still scarce, mainly relying on artificial neural networks. Although a single artificial intelligence method has demonstrated its powerful prediction potential, there are research gaps for the utilization of hybrid artificial intelligence algorithms to further improve the prediction capacity and accuracy of membrane fouling for membrane-based processes.

In terms of membrane performance, Hu et al. (2021) developed predictive methodologies for organic solvent nanofiltration (OSN) membrane performance using artificial intelligence. The study addresses the challenges in predicting the performance of organic solvent nanofiltration membranes due to the complex interactions between solvents, solutes, and membranes. Instead of relying on mathematical equations, the researchers compiled a large dataset with over 38,000 data points and employed artificial intelligence-based models for performance prediction. Through principal component analysis (PCA), the study identified the key parameters that significantly affect both the permeance and rejection of the membranes. The researchers trained three different artificial intelligence models, including artificial neural networks, support vector machines, and random forests, achieving high prediction accuracies of up to 98% for permeance and 91% for rejection. The findings of this research have important implications for data standardization, membrane design, and development. By utilizing artificial intelligence models, the industrial implementation of organic solvent nanofiltration can be fast-tracked, leading to improved process sustainability and efficiency. The study also highlights the need to overcome the challenges associated with predicting membrane performance in organic solvent nanofiltration, such as the diverse characteristics of solvents and the transient nature of nanofiltration membranes.

Liu et al. (2020a) aimed to predict the performance of polyvinylidene fluoride (PVDF), polyethersulfone (PES), and polysulfone (PSf) filtration membranes using machine learning. The study collected a comprehensive dataset of 1895 vectors, encompassing variables related to composition, fabrication, and operation. Regression models were developed to predict the performance of the membranes in terms of permeability and selectivity, achieving coefficients of determination ranging from 0.79 to 0.85. Classification models were also constructed to distinguish membranes with superior performance. The area under the receiver operating characteristic curve (AUC) ranged from 0.94 to 0.97 for classifying the top 20% and top 50% membranes, respectively. The research further investigated the impact of experimental structural information, such as porosity, thickness, surface contact angle, and roughness, on the predictive models. Including this additional information resulted in significant improvements in the regression models. An algorithm was developed and released to facilitate the development of advanced filtration membranes through virtual experiments. By utilizing machine learning and data mining techniques, the research demonstrated the potential for predicting membrane performance based on various parameters, enabling the rational design of membranes with enhanced properties. These findings contribute to reducing the development cost associated with the trial-and-error approach, ultimately leading to the production of more efficient and cost-effective filtration membranes.

In another study, Lin et al. (2017) investigated the removal of copper, nickel, and cobalt ions from synthetic mining wastewater using micellar-enhanced ultrafiltration and developed a Monte Carlo-based artificial neural network model to predict the micellar-enhanced ultrafiltration performance. The study examined the effects of surfactant-to-metal ratio and pH on metal rejection rate and permeate flux. The results showed that the model-predicted values agreed with experimental data, indicating the accuracy of the artificial neural network model. The surfactant-to-metal ratio and pH were found to have significant contributions to the metal rejection rate and permeate flux, with contributions ranging from 30 to 50%. Sampling time had a relatively lower contribution of 10%. The optimal conditions for micellar-enhanced ultrafiltration were determined to be a surfactant-to-metal ratio of 8.5 and a pH of 8–10, which resulted in rejection rates exceeding 99% for all three metals and compliance with Canadian environmental standards. During the experimental procedure, flux decrease, and concentration polarization effect were observed. The type of metal examined did not significantly affect micellar-enhanced ultrafiltration performance. Overall, the research concluded that the developed artificial neural network model could provide a valuable tool for predicting and understanding the micellar-enhanced ultrafiltration performance, while the Monte Carlo-based sensitivity analysis helped determine the relative importance of process parameters.

For removing biological oxygen demand (BOD) and chemical oxygen demand (COD) from polluted water, Zahmatkesh et al. (2022) aimed to assess the effectiveness of a novel ultrafiltration and mixed matrix membrane (MMM) composed of hydrous manganese oxide (HMO) and silver nanoparticles (Ag-NPs) in removing biological oxygen demand and chemical oxygen demand. The hydrous manganese oxide and silver nanoparticles content in the polycarbonate (PC) MMM was increased from 5 to 10%. A neural network was employed to compare PC-HMO and silver nanoparticles mixed matrix membranes. The mixed matrix membrane was evaluated in combination with hydrous manganese oxide and silver nanoparticle loadings to examine their effects on pure water flux, mean pore size, porosity, biological oxygen demand, and chemical oxygen demand removal efficacy. The artificial neural network model proved highly suitable for predicting biological oxygen demand and chemical oxygen demand removal. An ideal mixed matrix membrane model architecture was proposed with an optimal number of hidden layers (2 layers) and neurons (5–8 neurons). Experimental and predicted data showed strong correlations between the developed models. Biological oxygen demand was predicted with excellent R^2 and low root mean square error (RMSE) of 0.99 and 0.05%, respectively, while chemical oxygen demand was predicted with excellent R^2 and low RMSE of 0.99 and 0.09%, respectively.

In the case of the removal of dyes from water by using a membrane, Fetimi et al. (2021) focused on optimizing and predicting the removal of safranin-O cationic dye from aqueous solutions using the emulsion liquid membrane (ELM) technique. The study investigated various parameters, including surfactant content, internal phase concentration, dye concentration, and stirring speed, to determine their impact on dye removal. A total of 29 experiments were conducted. The researchers employed the response surface methodology (RSM) with Box–Behnken design (BBD) to optimize and predict the efficiency of the emulsion liquid membrane process. The optimized conditions resulted in 99.68% removal of Safranin-O within a contact time of less than 2 min. To forecast the removal of the dye, a novel approach combining an artificial neural network algorithm with particle swarm optimization (PSO) was proposed. The particle swarm optimization technique was used to determine the optimal parameter values for the artificial neural network. Overall, the study provided insights into optimizing the emulsion liquid membrane process for Safranin-O dye removal and demonstrated the effectiveness of the artificial neural network-particle swarm optimization hybrid model for predicting dye removal in aqueous solutions.

To assess the accuracy of artificial neural networks with other models in membrane assessment, Corbatón-Báguena et al. (2016) compared the performance of artificial neural networks with Hermia's models in assessing ultrafiltration of macromolecules using ceramic membranes. The multilayer perceptron artificial neural network was utilized, with operating parameters and dynamic fouling as inputs to predict permeate flux. The results showed that the artificial neural network simulations performed comparably to Hermia's models in terms of performance. Furthermore, the artificial neural network methodology demonstrated advantages in terms of computational speed, high accuracy, and ease of use compared to conventional mathematical models. The study highlighted the ability of artificial neural networks to learn and recognize trends in input and output data without prior assumptions, making them suitable for modeling complex nonlinear relationships. Previous applications of artificial neural networks in membrane technology have shown successful results in various filtration processes. In this research, the artificial neural network models accurately predicted permeate flux decline during crossflow ultrafiltration of macromolecules, providing a competitive, powerful, and fast alternative for dynamic ultrafiltration modeling.

Rall et al. (2020) tackled the challenge of optimizing membrane processes for cost-effective water treatment and disposal by integrating machine learning. Their proposed methodology combines artificial neural networks as surrogate models with deterministic global optimization, bridging the gap between nanoscale transport models and large-scale process design. The authors trained artificial neural networks using data from a one-dimensional extended Nernst-Planck ion transport model, extending it to a more accurate two-dimensional distribution for precise salt retention modeling. The open-source tools developed, encompassing process models and optimization solvers, enable resource-efficient multi-scale optimization in membrane science. The study underscores ion selectivity's importance in membrane technologies for sustainable water treatment and electrochemical processes. Despite the challenges in optimizing membrane transport, particularly in layer-by-layer nanofiltration, the research provides a novel approach. It suggests a hybrid methodology, combining data-driven surrogate models with mechanistic process models, to achieve multi-scale optimization and address the trade-off between computational efficiency and model fidelity. This integration of machine learning and mechanistic models offers insights into membrane synthesis and process design, enhancing water treatment and disposal practices.

For the improvement of gas separation using polymeric membranes, Hasnaoui et al. (2017) employed a regression model based on artificial neural networks to predict the permeability of oxygen, carbon dioxide, methane, and nitrogen for different polymers. Their dataset included 27 rubbery polymers and 122 glassy polymers, with 80% of the data used for model training. (Yampolskii et al. 1998) group's contribution theory was utilized to obtain 21 descriptors for the artificial neural network model. This approach resulted in more accurate predictions by the artificial neural network model for polymers with significant gas permeability compared to those with lower gas permeability. Inaccuracies in predicting lower gas permeability were attributed to errors in experimental measurements.

In addition, machine learning methods have been utilized in the field of polymers to predict various properties, such as the glass transition temperature (Kim et al. 2019a), dielectric constants (Kim et al. 2016), gas permeability (Barnett et al. 2020b), and the discovery of novel functional polymers (Wu et al. 2019b). One commonly used model for predicting polymer membrane performance is group contribution theory, which breaks down the chemical structure of a polymer into smaller fragments and employs these fragments as input features in machine learning models. Hierarchical methods have also been reported for fingerprinting polymers to predict properties, which have proven valuable in establishing structure–property relationships (Hasnaoui et al. 2017; Zhu et al. 2020; Yuan et al. 2021).

However, the gas permeability of a given polymer is often measured under different conditions, such as varying solvent treatments or degrees of aging. Machine learning models based solely on polymer fingerprints struggle to distinguish between these different conditions. The Polymer Gas Separation Membrane Database contains data for the gas permeability of the same polymer tested under diverse conditions in different laboratories and with different instruments. Therefore, relying solely on the chemical structure is insufficient to fill in missing values for gas permeability. To address this issue, a study conducted by Yuan et al. (2021) focused on using machine learning to impute missing gas permeability data for polymer membranes, which have potential applications in energy-efficient gas separations. The researchers utilized machine learning to impute missing values in the database and validated their approach against gas permeability measurements not recorded in the database. The study suggests that once the permeability of carbon dioxide and/or oxygen for a polymer has been measured, it becomes possible to quantitatively estimate most other gas permeabilities and selectivities, including carbon dioxide/methane and carbon dioxide/nitrogen. This early insight into the gas permeability of a new system can aid in identifying promising polymer membranes at the initial stage of experimental measurements.

In the case of mixed matrix membranes, Guan et al. (2022) demonstrated that an online random forest model can be trained for membrane-based carbon capture, leading to high-performance mixed matrix membranes for carbon capture. The models are trained for metal–organic frameworks (MOFs), which help overcome the permeability-selectivity trade-off. Experimental data match well with model predictions, and knowledge transfer from carbon dioxide/methane to carbon dioxide/nitrogen enables efficient and resource-saving learning. The researchers first train random forest models on literature data on carbon dioxide/methane separation, identifying the optimal metal–organic framework structure with a pore size of more than 1 nm and a surface area of 800 m^2g^{-1}. Then, representative metal–organic frameworks are blended into Pebax-2533 and a polymer of intrinsic microporosity-1 to fabricate mixed matrix membranes. The membranes demonstrate carbon dioxide separation performances that agree well with model prediction and surpass the 2008 Robeson upper bound. Additionally, knowledge transfer from carbon dioxide/methane to carbon dioxide/nitrogen separations shows better agreement with literature data compared to direct modeling, enabling efficient and resource-saving machine learning. This work applies machine learning to address domain-specific issues and may provide insights for other membrane development projects.

Gasós et al. (2023) discussed the development of surrogate models based on artificial neural networks for the optimization of membrane-based carbon dioxide separation processes. The goal is to overcome the computational challenges associated with traditional optimization methods. The surrogate models are designed to generate a Pareto front, which represents the optimal trade-off between process-specific electricity consumption and productivity. The researchers successfully developed surrogate models that can quickly generate the Pareto front within 200 ms. These models consider various input data such as membrane material properties, feed composition, and separation targets. The applicability of the models is demonstrated by creating process performance maps specifically for post-combustion carbon dioxide capture. The process performance maps provide valuable insights into the achievable gas separation regions in terms of carbon dioxide recovery and purity. They also highlight the influence of membrane material, feed composition, and separation targets on the optimal operating conditions and Pareto fronts. The study highlights the potential of using artificial neural networks as surrogate models for the optimization of membrane-based gas separation.

In another study, Zhao et al. (2023) aimed to establish a quantitative structure–property relationship (QSPR) model for predicting the gas separation performance of polyimide membranes using artificial neural networks. A data bank of 125 polyimides was used, and 20 descriptors were calculated for each polyimide. The number of groups in each polyimide was taken as the network input, and gas permeability was the output. Two neural network models, back-propagation (BP) and genetic algorithm-optimized back-propagation (GABP), were compared for prediction accuracy. The results showed that the genetic algorithm-optimized back-propagation model outperformed previous models and other machine learning approaches, with a root mean squared error of 0.44 for carbon dioxide. The genetic algorithm-optimized back-propagation model was found to apply not only to polyimides but also to copolyimides. It demonstrated satisfactory prediction capability for polyimides' gas separation performance, which can guide the synthesis and structure screening of polyimides, leading to resource-saving and commercialization opportunities. This research contributes to the development of efficient and cost-effective methods for designing polyimides with optimized gas separation properties, thereby supporting efforts to reduce greenhouse gas emissions and address climate change and energy security challenges.

Addressing the time-consuming and costly nature of polymer data for gas separation components is critical. In this regard, the Robeson upper bound serves as a well-known empirical criterion for selecting gas separation components. It illustrates the upper bound for permeability-selectivity relationships for various known polymers. Notably, polymers exceeding this upper bound are considered to have superior performance. However, manually recording polymer data through repetitive experiments is time-consuming and costly. Therefore, there is an urgent need for machine learning in this context. (Barnett et al. 2020a) trained a Gaussian process regression model to predict the performance of new polymers experimentally. To incorporate polymers into the machine learning model, a polymer fingerprinting algorithm was used to convert them into binary representations. This fingerprinting approach outperformed typical atom-type representations, as it efficiently accounted for chemical connectivity.

After rigorous testing and training using machine learning, polymers were accurately predicted based on data from the National Institute for Materials Science (NIMS) database. Over 11,000 polymers were screened, and more than 100 of them surpassed the Robeson upper bound. Further investigation revealed that polymers containing ether bonds, nitrogen rings, and sulfur groups were more likely to outperform other polymers, demonstrating a consistent physical pattern in the model's predictions (Yin et al. 2022). In conclusion, two polymers that exceeded the upper bound were successfully synthesized and tested.

Machine learning technology holds tremendous potential in the fields of membrane fabrication, permeability, and solute rejection. It offers a promising alternative to costly trial-and-error methods, ultimately improving the prediction of polymer features, streamlining membrane fabrication, and facilitating the development of novel polymers with a significant impact on membrane separation applications. Recently, artificial intelligence has gained prominence for its substantial role in optimizing various membrane applications, offering cost-effectiveness, ease of operation, highly predictable performance, and reduced energy consumption. Despite the significant benefits, there are also challenges associated with the application of machine learning in membrane design and discovery (L'Heureux et al. 2017, Barbiero et al. 2020, Molnar et al. 2020, Wang et al. 2020b, Maleki et al. 2022), as follows:

I. Computational resources: Training and running machine learning models can be computationally intensive, requiring substantial computational resources and time. Access to high-performance computing infrastructure becomes essential for conducting comprehensive analyses and optimizing membrane systems efficiently.
II. Availability and quality of data: Machine learning models rely on large, high-quality datasets for effective training. However, the availability of such datasets may be limited or even nonexistent for certain membrane systems. This lack of data poses a challenge in developing an accurate and robust mode.
III. Generalization: Models trained on specific datasets may struggle to generalize their predictions to new or unseen membrane systems. It is important to ensure that machine learning models can transfer knowledge

and generalize well to different systems, enabling their broader application.

IV. Interpretability: Some machine learning models lack interpretability, making it difficult to comprehend the underlying mechanisms behind their predictions. This lack of interpretability hinders the understanding of structure–property relationships, which is crucial for designing membranes with desired properties.

V. Multi-scale interactions: Membrane processes occur at various scales, from molecular interactions to macroscopic behavior. Integrating multi-scale information into machine learning models poses a challenge due to the diverse nature of relevant data.

VI. Transferability of models: Models developed for specific membrane materials or conditions may not easily generalize to different scenarios, impacting the broader applicability of machine learning in membrane design.

VII. Hybrid model challenges: Integrating machine learning with traditional mechanistic models (hybrid models) requires overcoming compatibility issues and ensuring synergy for enhanced predictive capabilities.

Types of membrane technology

Membrane technology offers a diverse range of solutions to address the separation, filtration, and purification needs of various industries. This technology comprises various types, including reverse osmosis, nanofiltration, and pervaporation, as depicted in Fig. 3, with each tailored to specific applications and requirements. A deep understanding of these diverse technologies empowers industries to streamline their processes, conserve resources, and maintain the production of high-quality products. Furthermore, ongoing research and development in the field holds the promise of pioneering

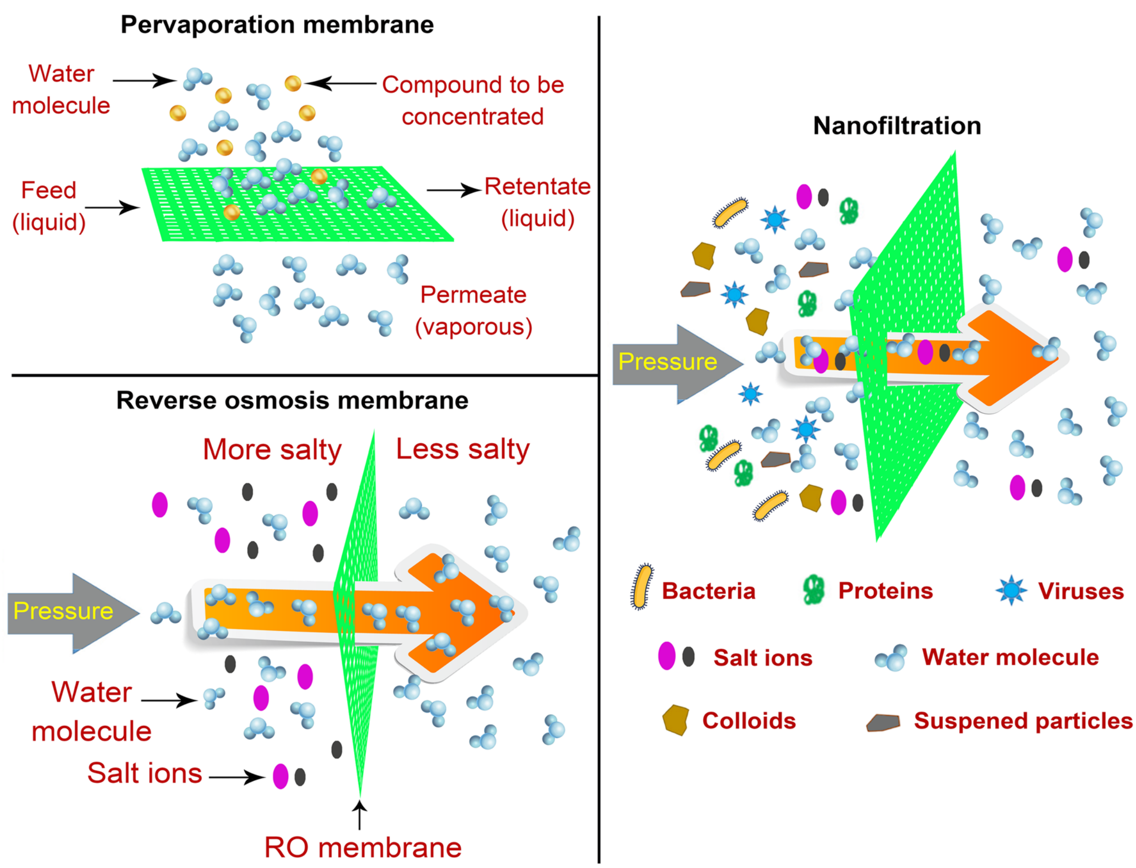

Fig. 3 A condensed overview of various membrane transport strategies, highlighting the pivotal influences of pressure and thermal-pressure gradients in facilitating transportation across membranes. The illustration emphasizes the role of pressure gradients in processes such as reverse osmosis and nanofiltration. Additionally, the figure visually captures the thermal-pressure-driven dynamics of pervaporation, showcasing the heating process at the membrane's feed side and the subsequent condensation occurring at the permeate side. This graphical representation distills complex membrane transport mechanisms, offering a visual guide to the interplay of pressure and thermal factors in these processes. In the figure, RO represents reverse osmosis

membrane technologies that will further enhance efficiency and sustainability across multiple sectors. These forthcoming technologies will play a pivotal role in improving the efficiency and sustainability of various industries, enabling them to meet the increasing demands for separation, filtration, and purification while minimizing resource consumption. Given its widespread applications in diverse fields, it is crucial to grasp the different types of membrane technology and their unique capabilities.

Reverse osmosis

Overview of the reverse osmosis process

Reverse osmosis plays a pivotal role in global desalination and water treatment. Its core purpose lies in generating clean water fit for purposes like agriculture, drinking, and various industrial applications, achieved by the efficient extraction of minerals, ions, and salts from the source water (McMordie Stoughton et al. 2013). Within the global desalination sector, reverse osmosis desalination plants take the lead, accounting for roughly 80% of all desalination facilities. This technology is particularly lauded for its effectiveness in purifying seawater and brackish water (Alsarayreh et al. 2020). Moreover, there has been a noteworthy trend toward the expansion of reverse osmosis plants, with certain facilities boasting a capacity exceeding 600,000 m^3 of water daily (Coutinho de Paula and Amaral 2017). Recently, reverse osmosis has become an indispensable process for water production, and numerous membrane fabrication techniques have gained widespread adoption.

As a natural process, the feedwater passes through a semipermeable membrane, moving from the lower salinity solution to the higher salinity solution until reaching equilibrium (Kim et al. 2019b). The fundamental concept behind the reverse osmosis process involves applying pressure that exceeds the osmotic pressure, causing the feedwater to flow through the semi-permeable membrane toward the medium with lower salt concentration, leaving the concentrated salt on the feed side and producing freshwater (Pangarkar et al. 2011). Globally, reverse osmosis has secured the majority of the desalination market due to its straightforward process and lower energy consumption when compared to other thermal-based desalination technologies (Matin et al. 2019). The features of reverse osmosis play a pivotal role in determining both the cost and the performance of the process.

The performance of the reverse osmosis membrane process is defined by a crucial metric known as specific energy consumption, which is primarily dependent on various operating conditions, including feedwater salinity, intake and disposal infrastructure, recovery rate, and energy recovery systems (Karabelas et al. 2018). Reverse osmosis, with energy costs ranging from 2 to 4 kWh/m^3, stands out as the most energy-efficient desalination technology, which is notably lower than other methods, making it highly regarded for this merit (Zarzo and Prats 2018; Matin et al. 2021). Furthermore, reverse osmosis demonstrates its effectiveness across a range of salinity levels, requires minimal space, and offers a straightforward and automated operation. Presently, reverse osmosis plants have capacities surpassing 60 metric tons per day, with an annual growth rate of 10–15%, resulting in a combined annual energy consumption of 100 terawatt-hours (Feria-Díaz et al. 2021). Importantly, the reduced energy consumption, coupled with advancements in system technologies, can lead to further cost reductions.

Figure 4 illustrates the functioning of a reverse osmosis water purification system, a technology extensively employed for the production of high-quality drinking water, particularly in regions characterized by arid or semi-arid conditions (Labella et al. 2021). These areas often face the challenge of source waters with elevated salinity concentrations. Reverse osmosis systems serve as effective solutions for this issue, as they excel at the removal of diverse impurities from the water source. The versatility of reverse osmosis systems is further emphasized by their capability to eliminate a broad spectrum of contaminants, such as dissolved solids, heavy metals, bacteria, viruses, and organic compounds. The merits of reverse osmosis systems extend beyond merely improving water quality. They go a step further by enhancing the taste and odor of the treated water. Additionally, they are adaptable and capable of meeting a wide array of water purification requirements. As a result, reverse osmosis systems play a crucial role in providing high-quality drinking water and addressing the distinct needs of various communities and regions.

The reverse osmosis desalination system comprises four subsystems, which are feed water pretreatment, high-pressure pump, membrane module, and permeate post-treatment (Shenvi et al. 2015). The pretreatment process is designed to eliminate suspended solids, microorganisms, colloidal matter, and other residuals that may result in scaling, fouling, and precocious membrane damage in consequence, optimizing the reverse osmosis process efficiency. The pretreatment process involves screening of feed water, filtration, coagulation/flocculation, pH adjustment, chlorination, ultrafiltration, and microfiltration. The choice of an appropriate pretreatment process depends on some parameters like reverse osmosis membrane requirements, feed water, and space availability (Hailemariam et al. 2020). Hence, the selection of the reaction monomer in interfacial polymerization can significantly impact the characteristics of nanofiltration membranes.

The pretreatment process has a substantial impact on membrane fouling in reverse osmosis. Fouling involves the unwanted deposition of substances within membrane pores or on their surface. Furthermore, fouling adversely affects

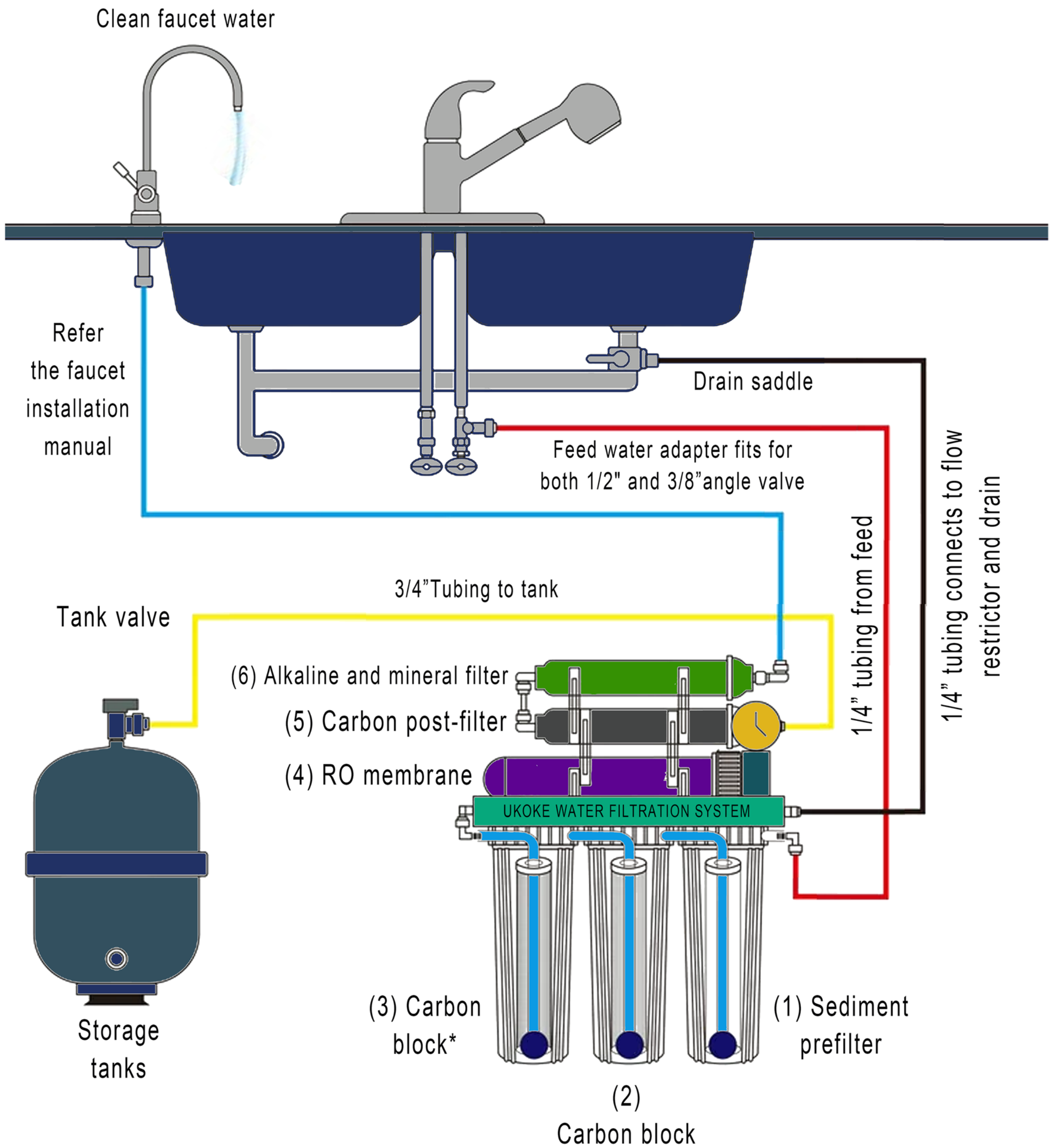

Fig. 4 Reverse osmosis water purification system. The reverse osmosis system begins with feed water entering at full pressure from the cold-water supply. The water passes through three pre-filters to remove sediment, chlorine, taste, and odor before reaching the reverse osmosis membrane (Stage 4). The automatic shut-off valve on the high-pressure side of the system responds to the incoming water pressure to allow water to proceed into the membrane housing. The reverse osmosis membrane filters out impurities and contaminants as water molecules pass through. A flow restrictor slows water flow to the drain, creating back pressure on the membrane for separation. The filtered water flows out of the check valve and into the automatic shut-off valve, with the check valve acting as a one-way barrier. The automatic shut-off valve on the low-pressure side responds to back pressure from the storage tank to create a seal and turn off the system when the tank is full. Filtered water is stored in a reverse osmosis storage tank until the faucet is turned on, at which point it passes through a post-carbon filter before reaching the user. In the figure, RO means reverse osmosis

the desalination process by increasing operational energy requirements and costs, as higher pressure is needed to maintain water flow, necessitating more frequent cleaning and reducing membrane lifespan. Membrane costs account for 13% of the total expenses (Anis et al. 2019). Membrane fouling is classified into inorganic fouling, organic fouling, colloidal fouling, and biofouling and can be efficiently diminished via the pretreatment process, except for biofouling, which needs further treatment via chlorination technique to deactivate the microbial growth in feed water.

Additionally, membrane fouling is significantly influenced by surface roughness; rougher surfaces are more susceptible to fouling as foulants adhere more easily to them than to smoother surfaces. To enhance fouling resistance, smoother membranes with a low negative charge and higher hydrophilicity are required (Hailemariam et al. 2020). High-pressure pumps supply the necessary pressure to push feedwater through the membrane, overcoming osmotic pressure. The required pressure varies depending on the feedwater type; for instance, it ranges from 17 to 27 bar for brackish water and from 55 to 82 bar for seawater (Al-Karaghouli et al. 2010). Hence, it is imperative to assess the quality of the feedwater to ensure appropriate pretreatment and pressure management.

Reverse osmosis plant involves pressurized pumping of feed water through a semi-permeable membrane to separate undesired materials while concentrating the stream (Mengesha and Sahu 2022). In the post-treatment process, the collected permeate was further subjected to pH adjustment or other steps such as re-carbonation, disinfection to restrict microbial growth, aeration to eliminate hydrogen sulfide, and degasification of carbon dioxide. Minerals enrichment can be done via chemical injection, for instance, calcium and magnesium.

Post-treatment is a vital process to prepare the treated water to meet the demands of water to be applied either in domestic or industrial fields. At the same time, membrane-cleaning agents and brine act as effluents that must be treated before being released into the ocean. However, chemical recovery is estimated to be economically unfavorable since the ratio between brine to chemicals is so huge. Additionally, chemicals must be diluted or neutralized to prevent damaging marine life (Shenvi et al. 2015; Skuse et al. 2021). Post-treatment mainly affects the operating costs depending on the productivity of clean water and the availability of sites for concentrate disposal.

Membrane materials and structures

There are various configurations for reverse osmosis membrane modules applied for large-scale plant applications, such as spiral wound modules, tubular, plate-and-frame, and hollow fiber, where the spiral wound module is the most prevalent membrane and an example of a conventional reverse osmosis process (Chung et al. 2014). Reverse osmosis typical types include cellulose acetate, thin-film composite, inorganic, and organic/inorganic hybrids (Zhao et al. 2021). Over 60 years ago, the first active membrane prepared for the reverse osmosis process was introduced by Reid and Breton (1959), a cellulosic acetate membrane using acetone as solvent via the phase inversion route. Cellulosic acetate membranes showed sufficient salt rejection at about 96%; nevertheless, the water permeance was extremely low at 0.03 L/m^2/h/bar, which was inappropriate for practical applications.

For the aim of developing water permeance without trading off salt rejection, Loeb and Sourirajan (1962) improved the membrane's water permeance by increasing the porosity of the cellulose film via utilizing pore-forming monomers and successfully fabricated cellulose diacetate membrane having asymmetric morphology and water permeance 0.14 L/m^2/h/bar besides 99% of salt rejection. However, cellulose diacetate membranes have drawbacks, including biological instability. Further development engendered cellulose triacetate membranes possessing higher biological, chemical, and thermal stabilities (Holloway et al. 2015), which surpass cellulose diacetate.

In terms of cross-section morphology, membranes are divided into two types: anisotropic (asymmetric) and isotropic (symmetric) membranes. Anisotropic membranes possess a heterogeneous composition in chemical composition and structure concurrently (Asad et al. 2020). Additionally, anisotropic membranes are categorized into composite membranes, for instance, self-assembled structures, thin-film and coated films, and phase-separation membranes known as Loeb-Sourirajan membranes (Nambikkattu et al. 2022), where composite membranes possess heterogeneous composition in chemical composition as well as structure. Unlike phase-separation membranes possess a homogenous chemical composition only, while the membranes' porosity, pore size, thickness, and structure differ from one to another (Buonomenna 2016; Duarte and Bordado 2016). On the other hand, isotropic membranes are remarked by the membranes' homogeneous composition, where the structure is fabricated by any single material. Furthermore, isotropic membranes are divided into nonporous, macroporous, electrically charged, and dense film membranes (Lee et al. 2016). A breakthrough in membrane technology has been achieved with the evolution of anisotropic membranes.

Cellulosic membranes are characterized by having anisotropic structures comprised of an upper-skin layer located on a porous sublayer where both have identical chemical compositions. Interestingly, the filtration performance mainly relies on the acetylation degree. Higher acetylation surprisingly enhances selectivity but dwindles water permeability. The stability of cellulosic acetate membranes is at pH 4–6 (Yang et al. 2019c). Therefore, in acidic and basic medium, hydrolysis reaction will occur and decrease selectivity.

Cadotte (1981) accomplished a milestone by fabricating polyamide thin-film composite membranes through interfacial polymerization between m-phenylenediamine and trimesoyl chloride on microporous polysulfone support. Incredibly, the fabricated polyamide thin-film composite membranes surpass cellulosic acetate in water permeance, which is 0.73 L/m^2/h/bar, and higher stability in acidic and basic medium but along with the same salt rejection of 99%. Moreover, the water permeance through thin-film composite membranes depends on the porous support layer features and the membrane surface's hydrophilicity; meanwhile, the surface charge and polyamide structure govern the salt rejection (Burns et al. 1979). Fabrication of thin-film composite membranes is considered a groundbreaking success in the desalination market.

Although polyamide thin-film composite membranes have significant performance and are mostly utilized membrane in the desalination market owing to thin-film composite membranes' astonishing salt rejection, mechanical strength, and water permeability, however, thin-film composite membranes face some challenges like low chlorine resistance and fouling (Zhao et al. 2021), while cellulosic acetate membranes still take part in a small market of desalination surpassing thin-film composite membranes in chlorine resistance with tolerance limit about 1 ppm (Shenvi et al. 2015). Nevertheless, many studies have been conducted for developing thin-film composites for chlorine tolerance.

Therefore, the merits of organic polymers can be highlighted in their simple processability, cost-effectiveness, and good selectivity. Additionally, organic membranes play a huge part in the desalination marker with a remarked activity in academic research as well as industrial-scale applications (Kayvani Fard et al. 2018). Inorganic membranes show outstanding thermal and chemical stabilities along with remarkable mechanical strength (Vasanth and Prasad 2019). Inorganic membranes encompass carbon-based membranes and metal oxide membranes, where zirconia, titania, alumina, and their mixtures are widely commercialized in the market of metal-oxide membranes. Inorganic membranes share the same structure comprising a support with a macro-porous structure and a barrier layer with a micro- or mesoporous structure. Inorganic membranes are commonly utilized in systems with challenging conditions to polymeric membranes as utilizing corrosive effluents and elevated temperatures (Saikia et al. 2019; Wills et al. 2019). Interestingly, inorganic membranes surpass polymeric membranes in the industry.

The synthesis of inorganic membranes from a highly advanced porous material, for example, graphene oxides and carbon nanotubes, marked the inorganic membranes as the most auspicious membranes in thin-film technology. Inorganic membranes have many merits, such as magnificent permeability and considerable selectivity, besides an effective performance in desalination processes (Yang et al. 2019c). Despite the high costs of inorganic membranes in comparison with polymeric membranes, inorganic membranes have a potent capability to withstand incessant backwashing and harsh chemical cleaning, sterilize and autoclave, and resist elevated temperatures up to nearly 500 °C. Additionally, inorganic membranes have a stable and well-defined pore structure and a prolonged lifetime (Kayvani Fard et al. 2018). However, their expensive costs and rigidity are the prime demerits of inorganic membranes.

Kumakiri et al. (2000) reported the earliest work on reverse osmosis using zeolitic membranes for water/mixture separation. The thickness of the membrane was found to be 5 μm with 0.4 nm pore size, leading to 44% of ethanol rejection. Li et al. (2004) described the use of zeolitic membranes for water/mixture separation in desalination utilizing reverse osmosis, where salt rejection achieved 76.4%. The diminishing in rejecting salt ability with increasing ionic strength is ascribed to the existence of two different types of pores in the zeolitic membranes: zeolite channel and microporous intercrystal pores.

Finally, mixed matrix membranes provide a significant platform for improving performance and flux, in addition to offering better antimicrobial characteristics. Mixed matrix membranes elucidate a remarkable enhancement in surface hydrophilicity, anti-fouling, and robustness (Kayvani Fard et al. 2018). Several synthesis methods have been conducted for the incorporation of nanomaterials within a polymer matrix, including phase inversion, blending, self-assembly of nanoparticles, and interfacial polymerization (Yin and Deng 2015). Therefore, the enhancement of organic membrane performance was unsurprising via the incorporation of inorganic nanomaterials.

Kwak et al. (2001) investigated the impact of titania filles on carboxylate group properties that functionalized thin-film composite membranes, and the results elucidate the vital role of carboxylate groups in the adsorption of titania on thin-film composite membrane's surface, which in turn generate remarkable anti-biofouling features, specifically under ultraviolet excitation. Although mixed matrix membranes acquire features of organic and inorganic membranes, the interface among the various materials can engender undesirable structures, therefore accompanied with difficulty in studying.

Advantages and challenges of reverse osmosis membrane technologies

Reverse osmosis membrane technologies have emerged as a highly effective method for water treatment and purification, offering numerous advantages in various applications. These membranes can remove a wide range of contaminants, producing high-quality water suitable for drinking, industrial use, and more. However, while reverse osmosis membranes provide significant benefits, they also present certain challenges that need to be addressed for optimal performance. Table 1 lists the advantages and challenges associated with reverse osmosis membrane technologies. Understanding these factors is crucial for harnessing the full potential of reverse osmosis membranes and advancing water purification techniques.

It is important to note that advancements in membrane technology and system design continue to address these

Table 1 Advantages and challenges of reverse osmosis membrane technologies. Reverse osmosis systems offer a compact design suitable for mobile water treatment and limited spaces, with enhanced energy efficiency. Their scalability accommodates diverse applications, providing high-quality water. Challenges include membrane fouling, concentrate disposal, high energy needs, and sensitivity to feedwater quality, emphasizing the importance of maintenance and pre-treatment

Reverse osmosis membrane technologies		References
Advantages	Compact footprint: When compared to other water treatment technologies, reverse osmosis systems have a comparatively compact design, needing less space. This qualifies them for installations where there is a need for mobility or where there is a need for restricted space, such as in mobile water treatment plants or emergency response units	Peters (2010), Abejón et al. (2015), Ruiz-García and Ruiz-Saavedra (2015), Jiang et al. (2018), Matin et al. (2019), Wang et al. (2019), Goh et al. (2022), Tavares et al. (2022)
	Energy efficiency: The energy efficiency of reverse osmosis membranes has increased because of technological improvements. Utilizing the difference in pressure between the feed and concentrate streams, energy recovery devices like pressure exchangers and energy transfer systems aid in lowering energy usage	
	Scalability: Reverse osmosis systems offer great design and capacity flexibility because of their high level of scalability. They may be modified to fit the requirements of a variety of applications, including tiny residential units and substantial industrial systems. Because of their scalability, they may be used in both centralized and decentralized water treatment systems	
	Versatility: Reverse osmosis membranes may be used with freshwater, brackish water, and a variety of other water sources. They are excellent for a variety of applications due to their adaptability, including desalination, water purification, and industrial process water treatment	
	Long service life: When properly operated and maintained, reverse osmosis membranes are meant to be robust and have a long service life. Maintenance such as membrane cleaning and replacement can assist in extending the lifespan and enhance performance	
	High water quality: Reverse osmosis membranes provide water that satisfies strict quality requirements. They successfully eliminate pollutants, leaving water free of contaminants, flavors, and smells. Clean water is frequently appropriate for industrial usage, drinking, and other purposes requiring high standards of water quality	
Challenges	Membrane fouling: Reverse osmosis membranes are susceptible to fouling, which is the buildup of particles, minerals, organic matter, or biofilms on the membrane surface. Fouling reduces efficiency and necessitates frequent maintenance or replacement. System performance and operational costs may be impacted by fouling	Greenlee et al. (2009), Alzahrani and Mohammad (2014), Shenvi et al. (2015), Wenten and Khoiruddin (2016), Schantz et al. (2018), Ainscough et al. (2021), Shehata et al. (2023)
	Concentrate disposal: The rejected solutes and contaminants are collected in a concentrated stream that is produced by reverse osmosis systems and is known as the reject or concentrate. To minimize any negative effects on the environment and guarantee that rules are being followed, this concentrate must be properly disposed of or managed	
	High energy needed: To counteract osmotic pressure and push water across the membrane, reverse osmosis processes usually need high operating pressures. Significant energy consumption may come from this, particularly in large-scale applications	
	Sensitivity to feedwater quality: The feedwater's quality can have an impact on how well reverse osmosis membranes work. Turbidity, suspended particles, and high concentrations of specific pollutants are some elements that might cause membrane fouling or deterioration, necessitating further pre-treatment procedures	
	Limited removal of some contaminants: While reverse osmosis membranes are effective at removing many contaminants, certain substances, such as volatile organic compounds (VOCs) and some pesticides, may not be completely removed through this process. Additional treatment steps may be required to address specific contaminants	

challenges, improving the efficiency, reliability, and overall performance of reverse osmosis membrane technologies.

Nanofiltration

Overview of the nanofiltration process

Nanofiltration (NF) is a membrane separation approach that has gained interest recently due to its distinct capabilities and applications. It is considered the most vital process in recently developed industrial processes (Nath et al. 2018). In the second half of the 1980s, nanofiltration emerged as a separate pressure-driven membrane approach for the removal of color, organic matter, and hardness from drinking water sources (Rana and Matsuura 2010; Mohammad et al. 2015). Nanofiltration serves as a bridging solution between reverse osmosis and ultrafiltration (UF) by targeting solute particle sizes in between, as shown in Fig. 5. Consequently, nanofiltration membrane may be rightly considered as a very 'tight' ultrafiltration or a very 'loose' reverse osmosis membrane. This process effectively excludes solutes of approximately 1 nm in size. Nanofiltration operates by allowing selective passage of components through a semipermeable membrane under a pressure gradient between the retentate and permeate. As a result, it enables the purification of components within this molecular weight range while separating them from higher molecular weight substances (Abdel-Fatah 2018; Nath et al. 2018).

These astonishing features allowed nanofiltration membranes to be conducted in various applications, for instance, water treatment, the food industry, the medical field, and the textile industry (Du et al. 2022). Since the first introduction of nanofiltration membranes, continual optimization and development has been done for nanofiltration membranes, along with improving the separation capability via tuning the material composition and the structural characteristics of nanofiltration membranes (Guo et al. 2022). Commercial nanofiltration membranes are distinguished by having a fixed charge that evolved by dissociation of ionizable groups such as carboxylic groups and sulfonic acid groups (Shon et al. 2013), which can significantly generate charges on the surface of the membrane as well as inside the membrane pores.

Moreover, these ionizable groups can be acidic or basic or a merger of both, which remarkably rely on the utilized materials in the fabrication process. Many factors influence the dissociation of such groups, for instance, the pH of the contacting solution, since the membrane's surface chemistry is labeled as amphoteric. Nevertheless, the membrane can exhibit an iso-electric point at a specific pH. Resulting of the valence ions and the fixed charges of the membrane, an inevitable electrostatic attraction or repulsion can take place. Two competing hypotheses explain the interaction's nature of solving energy barrier mechanisms and image

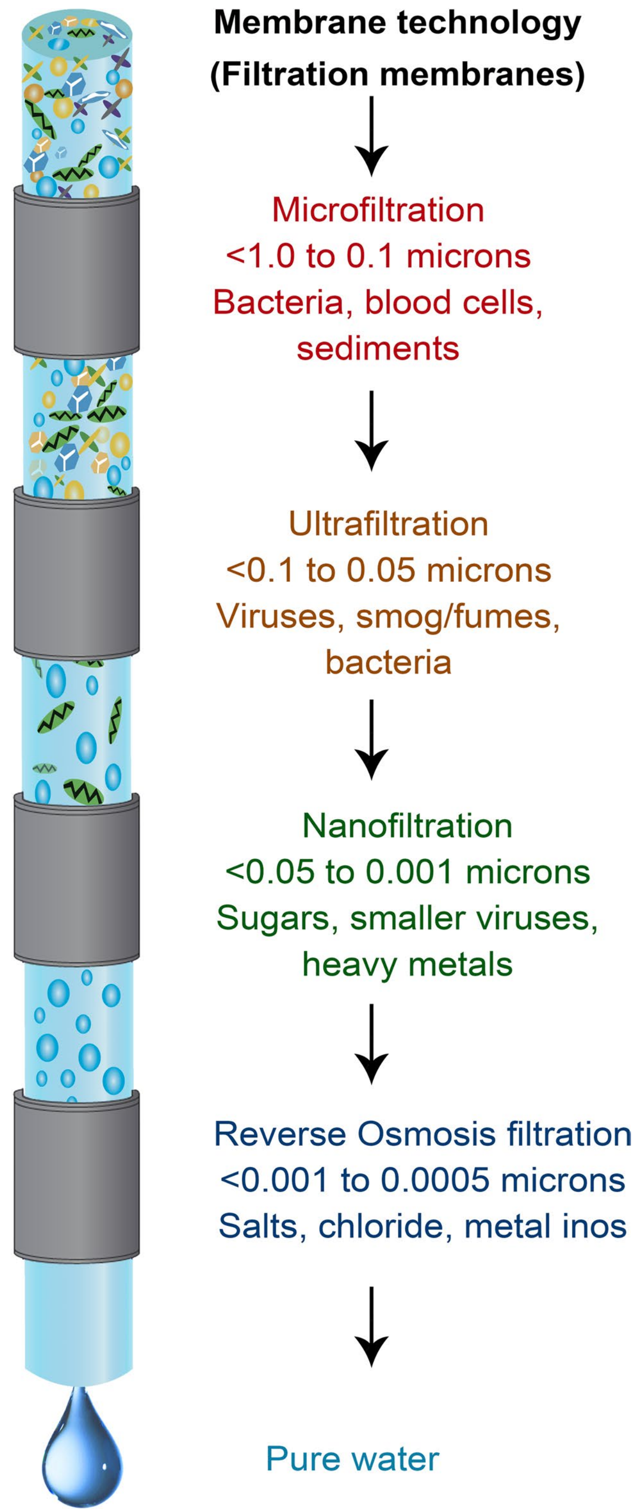

Fig. 5 Various membrane sizes employed in water and wastewater treatment. Schematically depicting pressure-driven membrane filtration, the rejection principle operates when species exceed the membrane's pore size under pressure. The removal efficiency of colloids, particles, and macromolecules is intricately linked to varying pore sizes. A comprehensive understanding of these variations is essential for optimizing water treatment processes, ensuring effective filtration, and maintaining water quality standards

forces phenomena. The separation mechanism of solutes via nanofiltration membranes is mainly attributed to steric hindrance, in addition to Donnan and dielectric effects (Tul Muntha et al. 2017). Noticeably, those are the processes that highly cause the successful rejection of solutes during nanofiltration.

Membrane materials and structures

Nanofiltration membranes' elective layer is identified with polymer chains possessing a three-dimensional network, where the filtration conductance is dominated by charges that exist on the layers and the pore size (Luo and Wan 2013). Several nanofiltration membranes have been developed in various separation techniques. Interestingly, many companies in the USA and Japan are pioneers in nanofiltration membrane commercialization (Aroon et al. 2010). However, various obstacles face nanofiltration membranes that need to be tackled for more utilization in demanding applications.

Apart from nanofiltration, membranes possessing molecular weight cut-offs lower than 500 Da are defined as tight nanofiltration, while nanofiltration membranes acquiring molecular weight cut-offs ranging from 500 to 2000 Da are known as loose nanofiltration, which has been employed in various applications such as sugar separation and polyphenol fractionation. Loose nanofiltration membranes have many characteristics, such as high separation selectivity toward smaller solutes, low salt rejection, and considerable permeability, which highlight loose nanofiltration as a promising membrane in resource recovery from wastewater and natural products. Tight nanofiltration membranes exhibit a stable performance and, therefore, are highlighted as broadly demanded in the desalination market. On the contrary, loose nanofiltration membranes are still limited in market demand (Guo et al. 2021). Thus, the development of the loose nanofiltration membranes' performance must be done urgently to meet the augmentation of practical needs.

The composite membrane method is the most efficient method for synthesizing nanofiltration membranes, where an ultrathin dense layer is fabricated over the porous substrate to engender a composite membrane; additionally, various methods can be applied for the synthesis of nanofiltration composite membranes (Choi et al. 2009). Interfacial polymerization, which takes place at two different immiscible phases' interfaces, has been commonly utilized. Moreover, the interfacial polymerization key is to decide the suitable reactant's diffusion rate and to adjust the partition coefficient of the reactant in two phases to obtain the ideal densification degree (Tul Muntha et al. 2017). As a result, the choice of reaction monomer in interfacial polymerization can indeed affect the characteristics of nanofiltration membranes.

Thin film composite (TFC) structures are the most broadly utilized Poly(vinyl)alcohol membranes encompassing a thin polyamide (PA) layer with a highly porous substrate layer such as polyethersulfone or polysulfone, as well as nonwoven support (Lau et al. 2012), as listed in Table 2, where the polyamides are generated via applying interfacial polymerization reaction. Noticeably, the fabricated polyamide layer has a crucial role in the separation performance of membranes, which is unfortunately restricted by the trade-off between membranes' selectivity and permeability (Yang et al. 2019b). To tackle such a drawback, several approaches were developed to enhance the separation efficiency of membranes.

For instance, the introduction of nanomaterials into the polyamide layers via utilizing interfacial polymerization reaction, producing thin film composite membranes (Lau et al. 2015). The inserted nanomaterials have introduced potent features like antimicrobial properties (Zhang et al. 2019); besides enhancing water permeability by creating huge nanochannels (Kim et al. 2019b), also, an effective method has also been developed via constructing an interlayer over the supported membrane to regulate the polyamide layer's characteristics and enhance the membrane separation performance. The incorporated interlayer can efficiently facilitate the fabrication of a high-quality polyamide layer and boost the water flux in the polyamide layer by functioning as a highly permeable gutter layer (Guo et al. 2022). Therefore, the resulting synergistic effects can significantly enhance water permeability and solute rejection.

Since day one, cellulosic-nanofiltration membranes have been widely commercialized and utilized in water purification (Thakur and Voicu 2016). For instance, they were utilized to purify drinking water from organic micropollutants (Narbaitz et al. 2013) in addition to encountering low fouling of membranes owing to the cellulosic materials' hydrophilicity. Nonetheless, cellulosic–membranes have a low bearing ability toward pH ranging from 2 to 8 and thermal change lower than 30 °C, resulting in limiting their applications (Lalia et al. 2013). Moreover, sulfonated polyethersulfone can be introduced as a rejection layer in some commercial nanofiltration membranes (Guo et al. 2022). As Zeng et al. (2017) reported, the presence of sulfonate groups can engender a negative charge on the membrane surface and, therefore, could aid in the rejection of anionic solutes with the aim of electrostatic repulsion. Table 2 lists some commercial membranes, along with their features and composition of selective top layer composition as defined by the manufacturer (Mohammad et al. 2015; Khairul Zaman et al. 2017).

Usually, there are two types of nanofiltration membranes: hollow-fiber membranes and flat-sheet membranes. Broadly, commercialized nanofiltration membranes are recognized as flat membranes as the composite membranes production process is only convenient for flat membranes. Noteworthy, commercial nanofiltration membranes are commonly

Table 2 Nanofiltration membranes. A compilation of cutting-edge nanofiltration membranes available in the commercial market, featuring details such as manufacturer, selective layer composition, and operational conditions. Notably, thin-film composite (TFC) membranes prevail in the current market due to their exceptional performance. Key polymers employed in nanofiltration membrane fabrication include polyamides, cellulose acetate, polyethersulfone, polypiperazine-amide, and poly(vinyl)alcohol

Membrane	Manufacturer	Composition of the selective layer	Stabilized salt rejection (%)	Molecular weight cut-off (Da)	Maximum temperature (°C)	pH range
TS80	TriSep, the USA	Polyamides (PA)	99	150	45	2–11
TS40	TriSep, the USA	Polypiperazine-amide	99	200	50	3–10
XN45	TriSep, the USA	Polyamides (PA)	95	500	45	2–11
NF270	Dow Filmtec, the USA	Thin film composite-polyamides (PA-TFC)	> 97	200–400	45	2–11
NF200	Dow Filmtec, the USA	Thin film composite-polyamides (PA-TFC)	(50–65) Calcium chloride ($CaCl_2$) (5) Atrazine(3) Magnesium sulfate ($MgSO_4$)	200–400	45	3–10
NF90	Dow Filmtec, the USA	Thin film composite-polyamides (PA-TFC)	(85–95) Sodium chloride (NaCl) (> 97) Calcium chloride ($CaCl_2$)	200–400	45	3–10
NF70	Dow Filmtec, the USA	Aromatic cross-linked polyamides	(> 95) Magnesium sulfate ($MgSO_4$)	200–300	45	3–9
NF45	Dow Filmtec, the USA	Polypiperazine-amide	(> 98) Magnesium sulfate ($MgSO_4$)	300	45	3–10
HL	GE-Osmonics, the USA	Cross-linked aromatic polyamides	(98) Magnesium sulfate ($MgSO_4$)	150–300	50	3–9
DK	GE-Osmonics, the USA	Polyamides (PA)	(98) Magnesium sulfate ($MgSO_4$)	200	50	3–9
DL	GE-Osmonics, the USA	Cross-linked aromatic polyamides	(96) Magnesium sulfate ($MgSO_4$)	150–300	90	1–11
CK	GE-Osmonics, the USA	Cellulose acetate	(94) Magnesium sulfate ($MgSO_4$)	2,000	30	5–6.5
Duracid	GE-Osmonics, the USA	Polyamides (PA)	(98) Magnesium sulfate ($MgSO_4$)	150–200	Not mentioned	0–9
NTR-729HF	Hydranautics, the USA	Poly(vinyl)alcohol/polyamides	(70) Sodium chloride (NaCl)	700	Not mentioned	2–12
ESNA1	Hydranautics, the USA	Composite polyamides	89	100–300	Not mentioned	2–10
NFG	Synder, the USA	Proprietary thin film composite- polyamides (PA-TFC)	(50) Magnesium sulfate ($MgSO_4$)(10) Sodium chloride (NaCl)	600–800	50	4–10
NFW	Synder, the USA	Proprietary thin film composite- polyamides (PA-TFC)	(97) Magnesium sulfate ($MgSO_4$) (40) (20) Sodium chloride (NaCl)	300–500	50	3–10.5
NFX	Synder, the USA	Proprietary thin film composite- polyamides (PA-TFC)	(99) Magnesium sulfate ($MgSO_4$) (40) Sodium chloride (NaCl)	150–300	50	3–10.5
SPIRAPRO	Koch, the USA	Proprietary thin film composite- polyamides (PA-TFC)	99	200	50	3–10
TFC SR100	Koch, the USA	Proprietary thin film composite- polyamides (PA-TFC)	99	200	50	4–10
SR3D	Koch, the USA	Proprietary thin film composite- polyamides (PA-TFC)	99	200	50	4–10
NP010	Microdyn Nadir, Germany	Polyethersulfone	(25–40) Sodium sulfate (Na_2SO_4)	Not mentioned	Not mentioned	1–14

Table 2 (continued)

Membrane	Manufacturer	Composition of the selective layer	Stabilized salt rejection (%)	Molecular weight cut-off (Da)	Maximum temperature (°C)	pH range
NP030	Microdyn Nadir, Germany	Polyethersulfone	(80–95) Sodium sulfate (Na_2SO_4)	Not mentioned	Not mentioned	1–14
ESNA1	Nitto-Denko, Switzerland	Composite polyamides	89	100–300	45	2–10
NTR7450	Nitto-Denko, Switzerland	Composite polyamides	50	600–800	40	2–14
UTC20	Toray, Japan	Polypiperazine-amide	60	180	35	3–10
TR60	Toray, Japan	Cross-linked polyamides composite	55	400	35	3–8
ES10	Nitto Denko, Japan	Aromatic polyamides	99.5	100	Not mentioned	Not mentioned

fabricated via interfacial polymerization (Emonds et al. 2020). At the same time, hollow-fiber membranes have a potent ability to supersede flat membranes in the future. Owing to outstanding features of hallow-fiber such as filling density and highly specific areas (Jye and Ismail 2017). However, the complexity of the fabrication process of hallow-fiber membranes, as well as their poor mechanical strength, made them unsuitable for high-pressure separation (Turken et al. 2019). However, the lower working pressure can lead to diminished specific energy consumption as reverse osmosis membranes.

Ceramic membranes also have gained considerable interest owing to the superior chemical and physical stabilities of these membranes. The sol–gel method is the most widely utilized approach for the fabrication of ceramic membranes. Alumina, titania, and zirconia are generally utilized as a selective layer in nanofiltration ceramic membranes (Yang et al. 2019c). During the fabrication of ceramic membranes, alumina acquires low chemical stability therefore preferred to be combined with more stable oxides like zirconia. There are various types of crystal phases in alumina, like α-alumina and γ-alumina, which are commonly utilized in ceramic membrane fabrication. γ-alumina membranes are unstable in acidic medium and have pore sizes close to ultrafiltration; therefore, γ-alumina is mostly utilized in gas separation (Du et al. 2022). Nevertheless, commercialized ceramic nanofiltration membranes are limited.

Anisah et al. (2020) fabricated a nanofiltration membrane on porous α-alumina support at 200 ℃. Noticeably, the membrane's pore size increased within elevating the sintering temperature up to 500 ℃. Additionally, for the development of ceramic membranes, microporous polymer frameworks have been introduced to alumina ceramic membranes to improve the organic solvent permeability. For instance, a previous study (Amirilargani et al. 2020) showed a reduction in the thickness of α-alumina membrane by 40 nm after modification via a porous organic framework, which in turn enhanced membrane permeability.

Advantages and challenges of nanofiltration membrane technologies

Nanofiltration membrane technologies have gained significant attention in various industries due to their unique capabilities in selective separation and water purification. These membranes offer several advantages, including selective removal of contaminants, high retention of divalent ions, moderate operating pressures, and versatility across different applications. Nanofiltration membranes are energy-efficient, environmentally friendly, and can enhance water quality by removing harmful substances. It is important to note that the specific advantages of nanofiltration membranes may vary depending on the application and the specific membrane properties. Analogous to reverse osmosis membranes, nanofiltration membrane has a strong separation capability toward small organic molecules and inorganic salts.

Interestingly, the key distinctive features of nanofiltration membranes are higher water flux than reverse osmosis membranes, low capability ranging from 10 to 30% for rejecting monovalent ions like sodium chloride, and a highly rejecting capability ranging from 80 to 100% for divalent ions such as sodium sulfate (Mohammad et al. 2015). Additionally, the nanofiltration process surpasses reverse osmosis in demanding lower operating pressure. However, nanofiltration is not suitable for the desalination of seawater, but more favorable to be involved in the pretreatment step as a hybrid method (Matin et al. 2019). Over the years, the nanofiltration application range has extensively enlarged and been highlighted as a promising technology. However, challenges such as membrane fouling, limited salt rejection, pressure requirements, membrane material compatibility, trade-offs between permeability and selectivity, energy intensity, cost considerations, and scaling/mineral precipitation need to be addressed for optimal performance and widespread adoption. Nanofiltration membranes proved their significant potential in wastewater treatment that is noteworthy to be applied. Unfortunately, the membrane fouling results in instabilities in operation that limit their applications. Also, many studies have been conducted for water recovery via nanofiltration membranes (Van der Bruggen et al. 2008), but in most cases, membrane fouling was the biggest potent issue that was vastly studied. Moreover, the concentration of the wastewater to be treated is another issue. Overcoming these challenges requires ongoing research and development efforts to improve membrane design, fouling control strategies, and system operation and maintenance practices. By capitalizing on the advantages and addressing the challenges, nanofiltration membrane technologies have the potential to revolutionize water treatment, industrial processes, and resource recovery. Addressing these challenges requires ongoing research and development efforts, technological advancements in membrane materials and designs, improved fouling control strategies, and optimized system operation and maintenance practices. Table 3 lists the advantages and challenges associated with nanofiltration membrane technologies.

Pervaporation

Overview of the pervaporation process

Pervaporation, another membrane process, has gained prominence as a powerful desalination technique. Kober invented pervaporation in 1917 when he discovered the selective permeation of water from albumin and toluene aqueous solutions employing films (Wang et al. 2013). Since that time, pervaporation has been investigated, eventually leading to its industrialization through the adoption of membrane manufacturers and the operation of pervaporation-hybrid processes. Pervaporation is widely recognized for its capacity to split binary or multi-component azeotropic mixtures by selective partial vaporization (Castro-Munoz et al. 2020), where the liquid mixtures are separated using molecular-sieving porous or dense membrane and vaporize downstream (Wang et al. 2016b). The prime driving force of pervaporation for permeate mass transfer is the vapor pressure differences through the membrane between the feed side and the permeate (Liu et al. 2021).

In comparison with other traditional separation techniques like adsorption and distillation, pervaporation shows potent competitiveness in the separation of azeotropic mixtures, organic-organic mixtures, and thermal-sensitive compounds, besides a considerable capability for the recovery of worthy diluted solutes from water (Zhuang et al. 2016; Zhou et al. 2017; Dong et al. 2020; Zhang et al. 2020b; Lu et al. 2022b). Pervaporation exhibits multiple characteristics, such as energy efficiency, exceptional selectivity, environmentally friendly operations, and cost-effectiveness. Moreover, pervaporation demonstrates strong integration capabilities with various processes. For instance, by integrating pervaporation with fermentation, it becomes possible to continuously remove targeted compounds like butanol and ethanol (Lu et al. 2022b), as shown in Fig. 6. Notably, the integration of these processes has shown significant improvements in performance quality (Jyothi et al. 2019).

Pervaporation can be conducted at atmospheric pressure utilizing a much lower temperature compared to distillation. When the downstream side operates at lower temperature and atmospheric pressure, defined as thermo-pervaporation and, in turn, engender activity differences that stimulate the mass transfer across the membrane. Thence, the process could be with relatively low-grade energy, which can be analogous to direct contact membrane distillation. Therefore, in the treatment of hypersaline effluents, the utilization of temperature difference is more recommended from energy aspects compared to reverse osmosis. Moreover, the introduction of thermo-pervaporation was many years ago (Eljaddi et al. 2021), but it has never been applied in the industrial field.

In developing pervaporation membranes, three crucial problems must be considered such as stability, productivity, and selectivity. Furthermore, the membranes' physical and chemical characteristics, as well as the permeating solutes interactions, are also critical for recognizing the separation technique and the membrane stability. Productivity is indeed impacted by the membrane's thickness (Figoli et al. 2015). However, the fabrication of pervaporation membranes having long-term stability and high performance is still a bottleneck step.

The mass transfer through pervaporation membranes is defined in three steps: (i) depending on the chemical affinity of the target molecules absorbed into the membrane's selective layer, (ii) diffusion of the molecules across the membrane in the vapor phase by the concentration gradient, (iii) desorption of vaporized molecules at the permeate side (Castro-Muñoz 2020). However, key operating parameters can influence its efficiency and selectivity. For instance, temperature plays a crucial role as it affects the vapor pressure and diffusion rate of the components (Trifunovic et al. 2006; Valentínyi et al. 2013). Higher temperatures generally enhance permeation rates but can also alter membrane selectivity. Feed composition, pressure, and membrane thickness are other variables that can be adjusted to optimize the separation performance. The choice of operating conditions depends on the specific application and the desired separation objectives.

Table 3 Advantages and challenges of nanofiltration membrane technologies. Nanofiltration membranes excel in retaining divalent ions, proving effective in water softening and desalination. Their selective separation ability removes specific pollutants while preserving desired elements, allowing for partial desalination at moderate pressures. Nanofiltration membranes are recognized as a green technology, reducing chemical usage. Challenges include membrane fouling, material compatibility, scaling, energy intensity, and balancing permeability and selectivity, addressed through regular cleaning, proper pretreatment, and ongoing energy-efficient research

Nanofiltration membrane technologies		References
Advantages	High retention of divalent ions: Reverse osmosis membranes are less effective at retaining divalent ions than nanofiltration membranes. This makes nanofiltration particularly helpful in processes like water softening and desalination, where the removal of hardness ions (such as calcium and magnesium) is necessary	Cadotte et al. (1988), Schäfer et al. (2004), Pinelo et al. (2009), Al-Zoubi et al. (2010), Mohammad et al. (2015), Ahsan and Imteaz (2019), Zhang et al. (2020a), Fatima et al. (2021), Tian et al. (2021), Bera et al. (2022), Elma et al. (2023), Maroufi and Hajilary (2023), Patel et al. (2023), Shehata et al. (2023), Zhang et al. (2023)
	Selective separation: A narrow range of pore sizes of nanofiltration membranes enables the selective separation of various solutes according to their size and charge. This makes it possible to eliminate certain pollutants while keeping desired elements like salts, divalent ions, or organic compounds	
	Partial desalination: Monovalent ions, such as salt and chloride, may be successfully removed by nanofiltration membranes while still allowing water molecules to flow through. Due to this characteristic, nanofiltration is useful for partial desalination, which reduces the salt concentration without completely removing all dissolved particles	
	Moderate operating pressure: In comparison with reverse osmosis membranes, nanofiltration membranes operate at lower pressures, which leads to less energy being used and lower costs for operation. This increases the energy efficiency and cost viability of nanofiltration for a variety of applications	
	Retention of natural organic matter: Natural organic matter, including humic substances and disinfection byproduct precursors, is retained well by nanofiltration membranes. Lowering the amount of potentially dangerous organic compounds aids in improving the water quality overall	
	Green technology: In comparison with conventional treatment procedures, nanofiltration membrane technologies often use fewer chemicals and generate less effluent. Because of this, nanofiltration is a more sustainable solution, fostering sustainability and lowering the total environmental effect of industrial operations	
	Versatility: Numerous sectors use nanofiltration membranes, including those that process water, produce food and beverages, make pharmaceuticals, and process chemicals. Because of its versatility, the separation process may be customized to meet particular requirements, and performance for various feed streams can be optimized	
	Reduced fouling potential: Due to its bigger pore size and greater permeability compared to reverse osmosis membranes, nanofiltration membranes have a decreased tendency to foul. Longer membrane lifespan, less frequent cleaning, and higher operational stability result from this	

Table 3 (continued)

Nanofiltration membrane technologies		References
Challenges	Membrane fouling: Fouling, which happens when suspended particles, organic debris, or scaling materials build up on the membrane surface or inside the membrane pores, is a problem for nanofiltration membranes. Fouling lowers permeate quality, lowers membrane performance, and uses more energy. Regular and efficient cleaning processes, the right pretreatment, the use of antiscalants, and fouling-resistant membranes are all necessary for fouling mitigation Membrane material compatibility: Nanofiltration membranes come in a variety of forms, including polymeric, ceramic, and hybrid membranes. However, for long-term performance and durability, the compatibility of the membrane material with the specific feed stream and operating conditions is essential. Specific membrane materials may be damaged or degraded by specific feed streams due to the presence of chemicals or extremely low pH levels Scaling and mineral precipitation: When feedwater contains significant amounts of hardness ions or other scaling compounds, nanofiltration membranes may be susceptible to scaling and mineral precipitation. Reduced permeate flow and deteriorated membrane performance can result from scaling. To avoid scaling and preserve membrane performance, proper pretreatment, antiscalant dosage, and cleaning techniques are crucial Energy intensity: Despite operating at lower pressures than reverse osmosis membranes, nanofiltration membranes still need energy input to overcome hydraulic resistance and produce the necessary separation. Particularly in large-scale applications, nanofiltration processes have the potential to use a substantial amount of energy. More work is being done to develop membranes and design systems that are more energy efficient The trade-off between permeability and selectivity: Permeability and selectivity must be balanced in nanofiltration membranes. Higher permeability membranes could have lesser selectivity, which would result in less effective separation. High selectivity membranes, on the other hand, may have lesser flux, which would reduce the process' total productivity. The performance of nanofiltration membrane systems must be maximized by achieving this balance	Al-Amoudi and Lovitt (2007), Van der Bruggen et al. (2008), Antony et al. (2011), Park et al. (2017), Labban et al. (2018), Nunes et al. (2020), Ahmad et al. (2021), Yang et al. (2021), Feng et al. (2022), Rolf et al. (2022), Yadav et al. (2022)

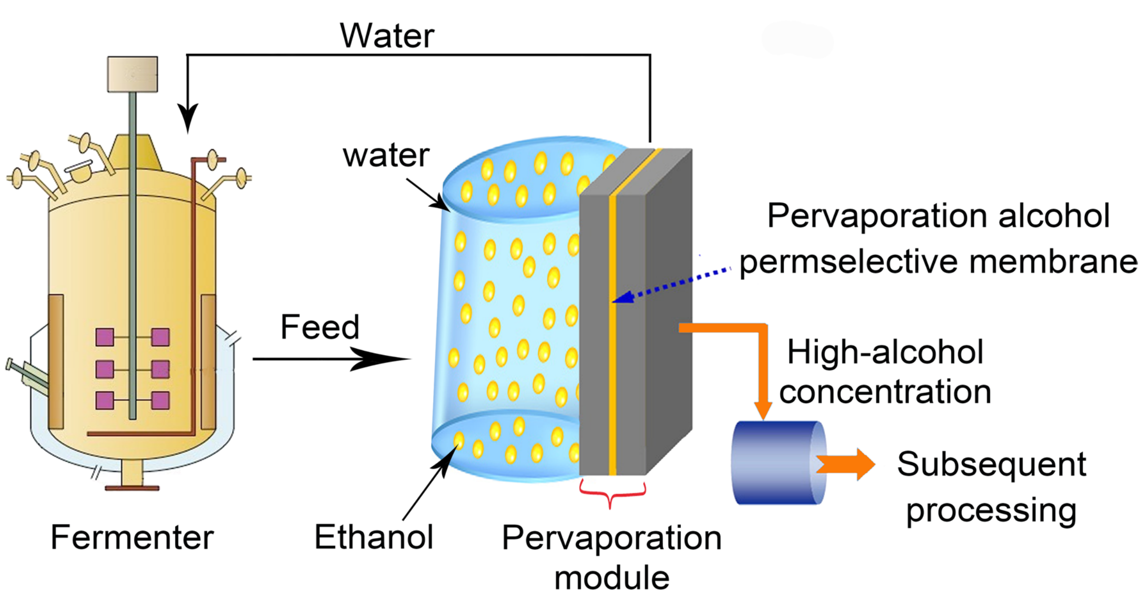

Fig. 6 Pervaporation membrane separation technique applied to an ethanol/water mixture. In this process, a selective membrane allows the preferential permeation of one component, typically ethanol, through its structure. As the mixture is exposed to a pressure gradient, vaporization occurs on one side of the membrane, followed by selective permeation and condensation on the other side. This technique enables the efficient separation of ethanol from water, finding applications in various industries, including biofuel production and chemical processing

Membrane materials and structures

Pervaporation membranes can be categorized into groups depending on the type of material utilized in the membrane: organic-permeable membranes and water-permeable membranes (Liu and Jin 2021a). Organic-permeable membranes are fabricated from hydrophobic materials and utilized for solvent recovery from solvent–water mixture or selective separation of solvent utilizing their membrane's different affinities. At the same time, water-permeable membranes are labeled as hydrophilic and utilized for solvent dehydration (Peng et al. 2021). Commonly, a higher feeding temperature ranging from 50 to 90 °C and applying vacuum on the permeated side are often required to elevate the driving force (Liu and Kentish 2018). The membrane's affinity toward a specific organic solvent over the other is a controlling factor in the separation process besides the withstanding of membranes in the solvent.

As earlier mentioned, membrane modules are categorized into four groups: plate-and-frame, tubular hallow-fiber, and spiral wound modules. Interestingly, plate-and-frame modules predominate the pervaporation process as they acquire flexible and simple configurations for cleaning, maintenance, and assembly. However, some drawbacks limit plate-and-frame module large-scale applications in the industry due to highly expensive costs and low packing density. Furthermore, a non-uniform flow path in a plate-and-frame module can generate an irregular mass transfer and premature fouling (Pal 2020). On the contrary, tubular modules have a high crossflow rate and uniform pathway. However, the highly expensive fabrication costs, low packing density, and hardness in encapsulation make them also as same as plate-and-frame modules (Brüschke 2006). Therefore, tubular modules are also inconvenient in industrial applications.

Recently, the spotlight shifted toward hallow-fiber and spiral wound modules, which considerably with lower fabrication costs and higher packing density. Since the pervaporation mainly includes phase change, hollow-fiber, and spiral-wound modules guarantee efficient flow in narrow channels of permeation and low-pressure loss. Spiral wound and hallow-fiber modules have been commonly recognized in the industrial field, and their a crucial role in large-scale applications (Lu et al. 2022a). Overall, the industrialization of pervaporation modules greatly relies on the module configurations and fabrication of effectively performing pervaporation modules.

Various types of membranes have been developed for pervaporation, such as polymers, ceramics, and mixed matrix membranes. Polymer membranes have been scrutinized as an auspicious membrane material for efficient dehydration of various organic mixtures, for example, ethylene glycol–water (Sun et al. 2015), acetone–water (Mangindaan et al. 2015), carboxylic acid–water (Sikander et al. 2022) and alcohol-water (Bolto et al. 2011), as mentioned in Table 4. Owing to the thermal-stable rigid polymeric chain structures, the polymeric membranes possess ideal selective sorption toward target molecules, as well as magnificent dehydration performance for organic liquids in aqueous mixtures (Raza et al. 2021). Polymeric membranes can perform as molecular sieves through the dehydration process and are accompanied by significant separation performance (Roy and Singha 2017). Therefore, hydrophilic membranes are sturdy toward water.

Hydrophilic membranes made from polymers, such as polyvinyl alcohol (PVA), cellulose, chitosan, polyimides, and polyacrylonitrile (PAN), are commonly employed in the dehydration of organic solvents through pervaporation. These membranes possess a surface that contains sorption centers capable of interacting with water molecules through ion–dipole, dipole–dipole, and hydrogen bonding interactions, thereby exhibiting water selectivity. Furthermore, water diffusion is facilitated by its smaller molecular size compared to other solvents. Ongoing research aims to modify the composition and structure of membranes to achieve optimal flux and separation factors. Polyvinyl alcohol is extensively utilized in the pervaporation dehydration of organic solvents due to its high hydrophilicity, ease of film formation, and favorable chemical and mechanical stability. Notably, research efforts concerning polyvinyl alcohol membranes focus on modeling and predicting the behavior of pervaporation processes, specifically in the dehydration of ethylene glycol (EG), utilizing thermodynamic equations (Rostovtseva et al. 2022). Many additional polymers, including polyether ketones, polybenzimidazole, polyamides, and perfluoropolymers, have also been found to have high promises for ethylene glycol dehydration. The impact of membrane structure on transport qualities was investigated in several studies since diffusion is one of the major components of high-water permselectivity. The pervaporation performance of the polymer membranes and mixed matrix membranes in EG dehydration is listed in Table 5.

Cellulosic membranes are widely utilized in reverse osmosis and pervaporation techniques owing to their highly hydrophilic ability and their polymeric chains with dense packing maintained by the aid of an intramolecular hydrogen bonds network. Several desalination pervaporation processes were performed for hydrated cellulose and bacterial cellulose produced from plant cellulose, either cotton or wood, while the latter was fabricated via surface cultivation of Acetobacter xylinum. The reported results by Kuznetsov et al. (2007) elucidated that irrespective of the precursor, these membranes effectively achieved 100% salt rejection at 40 °C with a salt solution of 40 g/L and acquired flux with 1.85 and 4.55 kg/m^2.h for bacterial and cotton cellulose, respectively.

Naim et al. (2015) fabricated a super-hydrophilic cellulosic acetate membrane through a phase inversion route. By

Table 4 Pervaporation performance of polymer membranes applied to organic solvent–water mixtures. It includes examples such as n-butanol-water, ethanol–water, isopropanol-water, acetic acid–water, and acetone–water, utilizing various polymer membranes like PDMS, PVDF, PTMSP, PAN, and PVC. The data include membrane type, temperature, organic solvent concentration in the feed, and total flux

Type of mixture	Example	Membrane material	Temperature (° C)	The organic solvent in feed (wt.%)	Total flux ($kg/m^2.h$)	References
Alcohol-water	n-Butanol-water	PDMS/PVDF	30	1	0.16	Jee and Lee (2014)
		PPhS/PDMS/PVDF	30	1	0.261	Jee and Lee (2014)
		PolyHFANB-base a-BCP81	60	1	3.5	Kim et al. (2015)
		PDMS/PAN/silicatite1	37	1	0.708	Li et al. (2014)
		PDMS/PhTMS/PVDF	40	1	0.704	Lee et al. (2020)
	Ethanol- water	PDMS-b-PPO	60	5	3.816	Liu et al. (2015)
		PTMSP-2	30	6	0.5	Volkov et al. (2004)
		PDMS	30	10	0.179	Ahmed et al. (2011)
		PDMS	37	6	0.75	He et al. (2020)
	Isopropanol- water	PDMS-b-PPO	60	5	3.65	Liu et al. (2015)
		PDMS	30	4	0.306	Shirazi et al. (2012)
Carboxylic acid–water	Acetic acid–water	PDMS-AMEO/PES	40	10	0.09	Hong et al. (2012)
		PDMS	35	10	0.057	Lu et al. (2000)
Ketone-water	Acetone–water	PVC/PS-F2.0	30	5	0.042	Samanta and Ray (2015)
		PAN/PDDA-ZrO_2/PSS-ZrO_2 flat sheet	30	5	1.24	Li et al. (2012)
		PPMS/CA	30	5	1.6	Luo et al. (2008)

Abbreviated expressions: PDMS: polydimethylsiloxane, PVDF: poly(vinylidenefluoride), PPhS: polyphenylsiloxane, HFANB: hydroxyhexafluoroisopropyl,, PAN: poly(acrylonitrile), PhTMS: phenyltrimethoxylsilane, PDMS-b-PPO: polydimethylsiloxane-block-polyphenylene oxide, PTMSP: poly[1-(trimethylsilyl)-1-propyne], AMEO: organic montmorillonite, PES: polyether polyethersulfone, PVC: polyvinyl chloride, PS: polystyrene, PAN: polyacrylonitrile, PDDA: Poly(diallyldimethylammonium chloride), and PPMS: polyphenylmethylsiloxane

inspecting the morphological structure of the membrane by scanning electron microscope, the result showed an asymmetric structure that guarantees a high flux and excellent salt rejection. The highest flux was recorded to reach 5.97 $kg/m^2.h$ via utilizing 40 g/L salt solution at 70 °C, and the salt rejection could surpass 99.9% even when applying a higher salt solution concentration of 140 g/L.

Inorganic membranes are found to be more efficacious than organic ones owing to their unique features, such as mechanical, thermal, and chemical stabilities. Zeolitic materials have undergone great progress owing to having a high tailoring feature in the aspects of adsorption capacity, selectivity, stability, and pore sizes. Silica-rich zeolites such as phillipsite, mordenite, or faujasites at relatively high temperatures are quite convenient to aid in obtaining long-term resistant material. Moreover, type A zeolites encompassing cations such as potassium in zeolite 3A, sodium in zeolite 4A, and calcium in zeolite 5A can perfectly produce highly hydrophilic materials (Cannilla et al. 2017). An example of hydrophilic zeolite is sodium alginate, utilized for the efficient dehydration of alcohols with a remarkable separation factor. At the same time, silicate-1 hydrophobic zeolite was applied for the elimination of organic solvents from water (Jose et al. 2020). Also, mixed matrix membranes are utilized in pervaporation applications and are the next-generation membranes.

For instance, porous magnesium oxide incorporated particles for dehydration of isopropanol via pervaporation resulted in higher selectivity. Zhao et al. (2009) fabricated Silica-reinforced polyelectrolyte complexes membrane exhibited efficient performance for the dehydration of isopropanol, where with 5 wt.% silica-loaded polyelectrolyte complexes, the membrane achieved a separation flux of 2.3 $kg/m^2.h$ at 75 °C and separation factor 1721 with 10% water as a feed composition in isopropanol.

Advantages and challenges of pervaporation membrane technologies

One of the notable advantages of pervaporation is its ability to integrate with other separation processes, enhancing overall efficiency and selectivity. Integration with distillation, for example, can significantly reduce energy consumption by using pervaporation to remove high boiling point components from the distillate (Babaie and Esfahany 2020; Do Thi et al. 2020). Pervaporation can also be combined with membrane distillation, creating a hybrid process known as membrane-enhanced vapor separation (Jyoti et al. 2015).

Table 5 Pervaporation performance of polymer membranes and mixed matrix membranes in ethylene glycol dehydration. Polymer membranes, including polyvinyl alcohol-based and mixed matrix membranes, demonstrate varying separation factors and total flux at different temperatures and ethylene glycol concentrations. The data highlight the potential of these membranes for efficient ethylene glycol dehydration applications under diverse conditions

Type	Polymer	Temperature (°C)	Ethylene glycol in Feed (wt.%)	Separation factor	Total flux ($kg/m^2.h$)	References
PVA-based membranes	PVA	25	90	354	0.12	Hyder and Chen (2009)
	FIPN50	75	97.1	148	10.63	Kuila et al. (2011)
	PVA (SO_3H-MIL-101-Cr)	70	90	2864	0.54	Zhang et al. (2017)
	PVA/MPTMS 50	70	80	311	0.07	Guo et al. (2007)
	PVA4 (TMC)	60	90	987	0.36	Hyder et al. (2009)
	PVA/PP/zeolite 4A (5%)	70	80	1,972	2.65	Shahverdi et al. (2013)
	PVA/NaA (5%)	70	80	1,520	0.96	Baheri et al. (2015)
	PVA10 wt.% HBPE	25	90	312	0.04	Sun et al. (2015)
	PVAm-PVA on PSf support/ CNT (0.5)	70	97	391	194	Hu et al. (2012)
	PVA/PP	60	80	1,021	0.91	Rezakazemi et al. (2011)
	PVA/PES (0.5 wt.% borax)	70	80	352	0.31	Guo et al. (2008)
Mixed matrix membranes	PBI/PEI	50	80	1925	0.70	Wang et al. (2011)
	(PEI/PAA)	22	95	450	0.01	Zhang et al. (2013)
	PPO/ HAS (5%)	50	90	11,240	0.02	Rostovtseva et al. (2020)
	PES-PD/PA/PD	38	89.5	220	0.25	Wu et al. (2015)
	(PEI/GO) 15 LbL	35	95	205	0.1	Halakoo and Feng (2020)
	CMS-3	30	95	2,419	0.02	Tang et al. (2017)
	SPEEK	30	90	2,991	0.10	Shao et al. (2005)
	PEC NPM/GO (3%)	60	90	1,191	0.96	Wu et al. (2019a)

Abbreviated expressions: FIPN: full interpenetrating network, MPTMS: γ-mercaptopropyltrimethoxysilane, TMC: trimesoyl chloride, PP: polypropylene, HBPE: hyperbranched polyester, PSf: polysulfone, CNT: carbon nanotube, PES: polyethersulfone, PBI: polybenzimidazole, PEI: polyetherimide, PAA: polyacrylic acid, PPO: poly(2,6-dimethyl-1,4-phenylene oxide), HAS: heteroarm star, PES: polyethersulfone, PD: polydopamine, PA: polyamide, GO: graphene oxide, LbL: layer-by-layer, CMS-3: perfluoropolymer, SPEEK: sulfonated poly(ether ketone), and PEC NP: polyelectrolyte complex nanoparticle

By integrating pervaporation with other unit operations, the overall process economics and environmental impact can be improved. Despite its advantages, pervaporation faces certain challenges that need to be addressed for wider commercialization. Membrane fouling, caused by the deposition of contaminants on the membrane surface, is a significant issue that affects separation efficiency (Li et al. 2023a, b). Fouling can be mitigated through membrane surface modification, regular cleaning protocols, or the use of antifouling coatings. Another challenge is the development of membranes with higher selectivity and stability under harsh operating conditions. Ongoing research focuses on the design of novel membrane materials and structures to overcome these challenges and improve pervaporation performance. Table 6 summarizes the advantages and challenges associated with pervaporation membrane technologies.

Applications of membrane technology

The technological progress in membranes has increased the implementation in multiple vital sectors such as water remediation, fuel cell, gas separation, biogas filtration, and the microalgae industry. According to the latest World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Programme (JMP) data, 2 billion people globally lack safe water access. Among them, 1.2 billion have basic services, 282 million have limited access, 367 million use unimproved sources, and 122 million consume potentially unsafe surface water (Balasooriya et al. 2023). Furthermore, untreated wastewater poses an alarming threat, with 80% of all wastewater released into the environment without adequate treatment (Sikder and Rahman 2023). In this context, membrane technology offers significant advantages. They provide effective filtration,

Table 6 Advantages and challenges associated with pervaporation membrane technologies. Pervaporation offers integration capabilities with other separation techniques, enhancing product quality and process efficiency. Environmentally friendly, it lowers energy and chemical usage, reducing carbon emissions. Energy-efficient and cost-effective, it selectively separates components and finds versatile applications. Challenges include membrane fouling, material compatibility, energy intensity, and pressure requirements, addressed through control strategies, durable membrane materials, optimized processes, and ongoing research for enhanced efficiency and sustainability

Pervaporation membrane technologies		References
Advantages	Integration capabilities: To improve total separation performance, pervaporation membranes can be used with other separation techniques like distillation or membrane distillation. This integration enables the improvement of product quality, energy savings, and process efficiency. Due to its compatibility with other separation methods, pervaporation has a wider range of applications and offers the potential for process intensification	Vane (2013), Bello et al. (2014), Kárászová et al. (2014), Jyoti et al. (2015), Nagy et al. (2015), Yi and Wan (2017), Tgarguifa et al. (2018), Babaie and Esfahany (2020), Do Thi et al. (2020), Castro-Muñoz et al. (2021), Zhu et al. (2021), Jafari et al. (2022), Pereira et al. (2022), Zhang et al. (2022a), Alonso-Riaño et al. (2023), Jiao et al. (2023)
	Environmentally friendly: By lowering energy use and chemical usage, pervaporation membrane technologies have benefits for the environment. Consequently, compared to conventional separation techniques, they help reduce carbon emissions and ecological footprint. Pervaporation is promoted as a more environmentally friendly alternative for many separation processes in industrial applications	
	Energy efficiency: Compared to conventional methods like distillation, pervaporation is an energy-efficient separation method. It consumes significantly less energy because it runs at relatively low pressures and temperatures. Pervaporation may achieve separation with less energy input by selectively evaporating the required component across the membrane, making it a more sustainable choice	
	Selective separation: Based on the variations in vapor pressure between the components, pervaporation membranes offer selective separation of liquid mixtures. This enables the effective removal of certain molecules while preserving the required substances, such as the separation of water from organic solvents. By selecting the proper membrane materials and operating conditions, pervaporation membrane selectivity may be tailored	
	Cost-effectiveness: Pervaporation membrane technologies can offer cost advantages in certain applications. They can reduce operational costs associated with energy consumption and chemical usage. Additionally, the continuous operation, scalability, and integration possibilities of pervaporation membranes contribute to improved process economics and overall cost-effectiveness	
	Versatility: Pervaporation membranes have several different uses in a variety of sectors. Volatile organic compound separation, solvent dehydration, gas purification, pollutant removal from water, and the recovery of valuable products from fermentation processes are all applications for them. Pervaporation membranes are flexible enough to accommodate various feed streams and separation needs	

Table 6 (continued)

Pervaporation membrane technologies		References
Challenges	Membrane fouling: Membrane fouling is a problem where unwanted substances accumulate on the membrane surface, causing reduced permeability and selectivity, reduced separation efficiency, and increased operational costs. Effective control strategies like membrane surface modification and regular cleaning are crucial to mitigate fouling issues	Shao and Huang (2007), An et al. (2011), De Guzman et al. (2011), Li et al. (2017), Li et al. (2019), Do Thi et al. (2020), Kim et al. (2020), Lecaros et al. (2021), Liu and Jin (2021b), Li et al. (2023a, b)
	Membrane material compatibility: The feed composition and operating conditions must be compatible with the pervaporation membranes. The membrane material may get degraded or damaged by certain substances or under certain conditions, which will affect the membrane's works and durability. Long-term operation and economic viability depend on the development of membrane materials with better durability, stability, and resistance to chemicals and harsh environments	
	Energy intensity: Although pervaporation is typically seen as an energy-efficient separation process, energy is still needed to maintain the required pressure and temperature levels. Energy consumption may be decreased by optimizing process factors, including temperature, pressure, and membrane thickness. The process' total energy efficiency can also be improved by looking at methods for combining pervaporation with energy recovery systems or renewable energy sources	
	Pressure requirements: Pervaporation processes typically require the application of a vacuum or the use of carrier gas on the permeated side to maintain the vapor pressure gradient across the membrane. Certain pressure requirements may be imposed as a result, which may have an impact on the overall process design and equipment costs. Research efforts are being made in the areas of developing membranes that may operate well at lower pressures and improving system designs to reduce pressure needs	

removing contaminants such as bacteria, viruses, and pollutants from water sources. Membrane filtration processes like reverse osmosis and ultrafiltration are highly efficient, producing clean and safe drinking water while minimizing the need for chemical treatments. These technologies play a vital role in providing access to clean water, particularly in areas facing water scarcity and contamination issues (Mallakpour et al. 2023).

Gas separation, on the other hand, has gained much attention, particularly in the context of greenhouse gas emissions. Notably, carbon dioxide (CO_2) emissions reached a record high of 33.1 gigatons in 2019, and reducing these emissions is a critical imperative in the fight against climate change (Salahodjaev et al. 2023). Membrane technology offers energy-efficient solutions for processes such as carbon capture and the purification of industrial gases (Qadeer et al. 2023). In this context, membrane gas separation allows for the selective separation of different gases based on their molecular size and properties. This technique is employed in various industries, including natural gas processing, hydrogen production, and carbon capture and storage. By utilizing membranes, the separation process becomes more energy-efficient and cost-effective compared to traditional methods such as cryogenic distillation. This not only reduces energy consumption but also lowers greenhouse gas emissions and contributes to environmental sustainability (Valappil et al. 2021).

In the realm of energy, the International Renewable Energy Agency (IREA) reports that renewable energy capacity reached 2537 GW in 2019, demonstrating the increasing shift toward sustainable energy sources (Hosseini 2020). Here, membrane technology plays a crucial role in enhancing energy production efficiency, with applications spanning from fuel cell membranes to biodiesel separation and the purification of biogas (Garg et al. 2023; Nimir et al. 2023; Wojnarova et al. 2023). For instance, in fuel cells, membranes enable the efficient conversion of chemical energy into electrical energy by facilitating the transport of ions while preventing the mixing of reactants (Tanveer et al. 2021). Additionally, membrane-based systems, such as membrane reactors, are used in various energy-intensive processes, including hydrogen production (Osat et al. 2022; Liang et al. 2023) and carbon dioxide capture (Dey et al. 2023; Wang et al. 2023c). These technologies enhance energy efficiency, reduce greenhouse gas emissions, and contribute to the transition toward renewable and sustainable energy sources.

The microalgae industry, a promising frontline in bioprocessing, presents yet another field where membrane technology is poised to revolutionize sustainable bioproducts.

Membranes facilitate microalgae cultivation and harvesting, enable the formation of biofilms, and aid in the refinement of high-value bioactive compounds (Huang et al. 2023). Membrane photobioreactors (MPBRs), which combine membrane filtration and photobioreactors, can create a controlled environment for microalgae growth, offer efficient nutrient supply, prevent contamination, and increase biomass productivity. It also reduces reliance on chemical solvents and waste generation, aligning with green, sustainable, and energy-saving bioprocessing principles (Gerardo et al. 2014; Banerjee et al. 2023).

Water treatment and desalination

Desalination technologies have experienced significant growth since 1928, when desalination plants first emerged in water-stressed cities worldwide. The development of various techniques, such as multi-effect distillation, multi-stage flash distillation, and reverse osmosis, has led to improved conditions for freshwater production, particularly in membrane-based desalination technologies like reverse osmosis. These advancements have made desalination an increasingly attractive option for providing municipal water supply by effectively removing salt from seawater at a more affordable cost. As a result, the number and size of desalination plants globally have been steadily increasing at an average annual rate of 6.8% since 2010. This growth corresponds to an average annual addition of approximately 4.6 million m^3/day of production capacity. In the period from January 2019 to February 2020, a total of 155 new desalination plants were contracted and installed worldwide, contributing an additional installed capacity of 5.2 million m^3/day. As of July 2016, the cumulative global desalination capacity for freshwater production reached 95.6 million m^3/day, encompassing 18,983 plants and projects. By the end of 2017, the cumulative desalination capacity worldwide had increased to 99.8 million m^3/day, considering plants built since 1965. The operating capacity of installed plants was estimated to be 93% of the installed capacity at that time. As of mid-February 2020, the global installed and cumulative desalination capacities for freshwater production stood at 97.2 million m^3/day and 114.9 million m^3/day, respectively, with 20,971 projects in progress. Out of these projects, 16,876 were installed plants (Jones et al. 2019; Eke et al. 2020; Do Thi et al. 2021). Saudi Arabia, the United Arab Emirates, Kuwait, and Qatar account for 55% of total worldwide desalination capacity. Desalination plants for urban water are found all over the world but are particularly prevalent in the Middle East and North Africa. Middle East and North Africa had the biggest regional desalination market in 2019, accounting for approximately 45.32% of total capacity, followed by East Asia and the Pacific (17.52%), North America (11.34%), and Western Europe (8.75%). Southern Asia (2.94%), Eastern Europe and Central Asia (2.26%), and Sub-Saharan Africa (1.78%) have the lowest regional desalination capacity, with desalination primarily restricted to modest plants for private and industrial purposes (Do Thi et al. 2021).

Because of its lower cost, lower energy requirement, and improved membrane durability, RO desalination has seen a significant increase in use. Reverse osmosis desalination facilities are critical in alleviating water scarcity in coastal areas across the world (Pan et al. 2020; Lim et al. 2021; Zhang et al. 2022b). Additionally, nanofiltration and pervaporation membranes are integral components in addressing water scarcity and pollution challenges through wastewater treatment and desalination. Nanofiltration membranes exhibit selective permeability, effectively eliminating contaminants like suspended solids, organic matter, bacteria, and some viruses from wastewater and brackish water sources. Operating at low pressures, these membranes ensure high rejection rates while permitting the passage of smaller ions, making them ideal for water softening, odor removal, and addressing emerging pollutants (Abdel-Fatah 2018; Joseph et al. 2023; Lee et al. 2023).

Pervaporation membranes excel in separating volatile organic compounds and treating concentrated industrial wastewater (Kujawa et al. 2015; Wang et al. 2020a). Using a combination of evaporation and vapor-phase diffusion, they efficiently remove volatile contaminants, boasting advantages such as low energy consumption, compact design, and adaptability to varying feed concentrations (Peng et al. 2003). In desalination, nanofiltration membranes remove divalent ions and larger molecules, producing high-quality water while retaining valuable salts. Pervaporation membranes selectively separate water from dissolved salts, offering an energy-efficient desalination alternative by exploiting temperature and concentration gradients, leaving behind concentrated brine for further treatment (Wang et al. 2018; Prihatiningtyas and Van der Bruggen 2020; Eljaddi et al. 2021; Li et al. 2023a, b).

Removal of pollutants

Membrane technology has exhibited great results in removing many ubiquitous contaminants like dyes, pharmaceutical products, heavy metals, etc. In one attempt, Kang et al. (2020) aimed to address the challenge of separating dyes utilizing nanofiltration membranes by fabricating a loose nano-filtration from poly piperazine amide membrane with a pore size larger than nanofiltration and lower than ultrafiltration. A significant effect of the electrospray time on membrane permeability was observed where it dropped from 108.7 to 4.7 LMH/bar when the electrospray time elevated from 5 to 120 min, respectively. This observation is likely attributed to the increase in electrospray time leading to a thicker membrane, which spontaneously declines its permeability. The significantly higher permeability of methylene blue compared to both Congo red and Evans blue could be attributed to the strong Coulombic interactions between the negative-active species of the polypiperazine amide membrane and the cationic methylene blue that directly facilitates the grasp of methylene blue molecules by the membrane. Furthermore, the rejection of methylene blue (below 90%) was lower than that of Congo red and Evans blue (above 99%), which may be due to the effect of size sieving and the cationic character of methylene blue decreasing the Donnan effect (Wang et al. 2016a). In one word, the potential of loose nanofiltration membranes for the effective separation of dyes offers valuable insights into their application in water treatment and contaminant removal.

In the textile industry, nanofiltration finds applications in the treatment of wastewater generated during dyeing and printing processes. It efficiently removes reactive dyes, salts, and dye intermediates, allowing for the recovery of water and valuable compounds and ensuring compliance with environmental regulations. Similarly, in the clothing and leather industry, nanofiltration plays a vital role in water recovery, salt removal, and the treatment of effluents to minimize environmental impact (Ahmad et al. 2022; Du et al. 2022). Due to the selective separation of the dyes and inorganic salts, as well as the reduction in chemical oxygen demand and biochemical oxygen demand, recent studies have shown that the nanofiltration membrane is a competitive separation and purification process for the wastewater treatment of the textile industry (Lin et al. 2015, 2016; Han et al. 2018; Kumar et al. 2022; Zheng et al. 2022; Dou et al. 2023; Rendón-Castrillón et al. 2023; Setiawan et al. 2023).

The sustainable concept of recovering dyes and salt solutions from textile effluent could be materialized with a nanofiltration membrane. In this context, the use of hollow fiber loose polyethersulfone nanofiltration membrane was demonstrated by Chu et al. (2020) to achieve high fractionation efficiency of dye/salt mixtures, with Congo red dye (0.1 g/L) being rejected up to 99.9% of the time while allowing more than 93% of sodium chloride salt (1 g/L) to pass through the membrane. The potential of loose nanofiltration to recover dyes and salt solutions in textile wastewater treatment is highlighted by their results. In the context of real textile wastewater treatment, Tavangar et al. (2019) investigated the treatment of real textile wastewater using electrocoagulation (EC) and nanofiltration processes, as well as their hybridization (EC-NF). The electrocoagulation pretreatment was performed using different electrode materials, with the aluminum electrode being superior in achieving 64% and 94% of chemical oxygen demand and color removal, respectively. A loose nanofiltration membrane (NP010, Microdyn Nadir) was applied for the nanofiltration process, providing resource recovery through high retention of dyes and permeation of inorganic salts. The nanofiltration membrane had great removal of color (> 87%) and ultralow rejections of inorganic salts (< 4%). The hybridization of EC-NF could augment each other's strengths and mitigate their individual drawbacks. The nanofiltration membrane could eliminate strong color from left-over electrocoagulation-treated solutions and enhance overall performance. Electrocoagulation has been integrated as a pretreatment step that considerably boosted membrane flux to reach 15 L/m^2.h with a flux recovery ratio of 67.99% of nanofiltration, where in comparison with stand-alone nanofiltration, the flux was found to be 2 L/m^2.h and recovery ratio 11.68%. Therefore, the electrocoagulation process as pretreatment could reduce membrane fouling and increase the permeate flux of the nanofiltration membrane. Finally, the hybridization of EC-NF may possess excellent potential for real textile wastewater treatment and efficient fractionation of dye/inorganic salts.

The elimination of sulfates, the recovery of valuable chemicals, and the decrease of chemical consumption in the bleaching process are all advantages of nanofiltration for the paper and pulp sector. The nanofiltration technology helps to enhance the quality of product streams and minimizes the industry’s environmental impact by selectively separating dissolved organics and colorants. Nanofiltration is used in the chemical and fine chemistry industries to purify intermediates and final products, get rid of contaminants, and treatment of wastewater (Mänttäri et al. 2021). Within this context, Lastra et al. (2004) aimed to remove complexed metals from a chelate stage effluent in a chlorine-free bleaching plant, allowing for the recycling of the permeate as make-up water to the same bleaching stage. The main industrial benefits include decreased freshwater consumption in the pulp mill and a significant reduction in effluent discharge. Two composite aromatic polyamide membranes and a ceramic membrane were tested on a pilot scale at the pulp mill to assess the viability of the nanofiltration process for industrial application. The polymeric membranes exhibited better performance than the ceramic membrane in terms of rejection and fouling, but the permeation rates were comparable. Essentially, complete rejection (99–100% of iron and manganese) was achieved for volume reduction factors up to 7. The recovery in the permeate stream is equivalent to 86% of the original wastewater.

In another attempt regarding the removal the detrimental dyes from wastewater, Rambabu et al. (2019) developed a polyethersulfone/polyethylene glycol membrane with a varied mass percentage of calcium chloride. The results of contact angle measurement and water uptake exhibited the influence role of calcium chloride in developing the hydrophilicity of the polyethersulfone/polyethylene glycol membrane. Hence, the wettability of the as-prepared membrane promoted and directly boosted its permanence. This finding agreed with Ghandashtani et al. (2015) study that proved the outstanding impact of embedding silicon dioxide into polyethersulfone on boosting the membrane's hydrophilicity. In addition, the fouling of the calcium chloride-modified polyethersulfone/polyethylene glycol membranes was less than the neat polyethersulfone membrane.

The separation efficiency of the fabricated membranes was examined toward anionic dyes (Congo red and Orange II) and cationic dyes (methylene blue and crystal violet), denoted that the optimal calcium chloride proportion was 10 wt.%. This calcium chloride proportions showed superior filtration properties of rejection and flux owing to its smaller pore size of 3.6 nm and plentiful negative charges on the surface (21.8 mV). Noteworthy, the unmodified polyethersulfone/polyethylene glycol membrane revealed the highest rejection and least permeability compared to the modified membranes, which inferred the inappropriateness of the unmodified membrane for dye separation. This conclusion was consistent with Idris et al. (2007). Accordingly, embedding inorganic particles into the membrane matrix could develop the characteristics of membrane hydrophilicity, mechanical durability, and water flux, which drastically improve the separation performance and fouling resistance.

In another investigation, Albatrni et al. (2021) attained a superb removal % of mercury (II) of 99% using a polyvinyl amine ultrafiltration membrane. Such promising results are due to the potent interactions between mercury (II) and the active species of the as-fabricated membrane; (i) the plentiful amine groups of the membrane could bond to mercury (II) via outer-sphere complexation. (ii) The possible coordination bond between amine groups and mercury (II), which is the predominant mechanism based on the results of conductometric titration. Expectingly, the existence of sodium chloride and sodium sulfate affects the rejection percentage of mercury, where the rejection % attained 90% when their concentrations were 5000 and 650 mg/L, subsequently. While the over-increasing in the sodium chloride concentrations to 250,000 mg/L, gives rise to a decline in the mercury rejection % to 50%. This performance is most probably because of the resultant mercuro-chloro complex.

In conclusion, membrane technology is a promising solution to overcome the notorious contaminates from wastewater, such as dyes and heavy metals that are drained from bountiful industries. The interaction mechanism between the membrane and pollutants controls the efficacy of the removal process. Nevertheless, the size of membrane pores limits the use of this technology in some cases since the pollutants could penetrate through these loose pores. Accordingly, pioneering research papers have targeted fabricating a loose nanofiltration with a pore size larger than nanofiltration and lower than ultra-filtration.

Removal of nutrients

Indubitably, the nutrient existence in drinking water harmfully influences human health since it causes deterioration of blood cells and the intestine, as well as kidney and liver failure. Consequently, continuous investigations have been executed to outdo the jeopardy of these detrimental pollutants. Interestingly, membranes have disclosed individual capability in removing nutrients.

Growing attention is being directed toward forward osmosis membrane technology, which is considered a promising method for a membrane process with low fouling. It is also seen as a novel approach for the extraction and retrieval of nutrients from wastewater and sludge (Jafarinejad 2021). In this regard, Zhang et al. (2014) investigated the feasibility of using a forward osmosis dewatering process for nutrient recovery from source-separated urine. The filtration process showed high water fluxes of up to 20 L/m^2.h when the active layer faced the feed solution. The rejection rates for neutral organic nitrogen (urea-nitrogen) in fresh urine were relatively low, but improved rejection rates were observed for ammonium (50–80%) in hydrolyzed urine and phosphate and potassium (> 90%) in most cases. Compared to the simulation based on the solution-diffusion mechanism, higher water flux, and solute flux were obtained using fresh or hydrolyzed urine as the feed, attributed to intensive forward nutrient permeation. The study concluded that the forward osmosis process was cost-effective and environmentally friendly for nutrient recovery from urban wastewater at the source.

In another study, Jafarinejad et al. (2019) aimed to concentrate ammonium in wastewater using a surface-modified nanofiltration membrane operating in forward osmosis mode. The modified membranes showed improved ammonium rejection rates. For synthetic ammonium solutions, the rejection rate was greater than 99% for the modified membranes compared to 75.5% for the original membranes. When treating real wastewater, the rejection rate declined to 89.3% but still showed significant improvement compared to the virgin membrane. The surface modification of the membranes involved grafting polyethylenimine on the polyamide thin film composite membrane using dicyclohexylcarbodiimide as a cross-linking agent. The modified membranes exhibited improved water flux and reduced reverse solute flux for certain ions. Overall, the study demonstrated the potential of polyethylenimine-modified membranes for the concentration and reuse of ammonium from wastewater sources.

Teoh et al. (2022) focused on using membrane distillation for water purification and nutrient recovery from aquaculture wastewater. The study found that the polyvinylidene fluoride membrane with micro-structures exhibited excellent superhydrophobic properties with a water contact angle of 153.3°. The continuous separation and treatment of fish farm wastewater showed a small and steady flux reduction of 1.4 kg/m^2·h, indicating low fouling. The batch process of feed concentration achieved a water recovery of 86.3%, with the retentate concentration of fish farm water being at least five times higher than the initial concentrations of ammonia (16.4 to 82.2 mg/L), phosphate (18.0 to 99.8 mg/L), and potassium (68.0 to 384.8 mg/L). The rejection of all selected inorganic substances, except for ammonia (> 86%), was higher than 99%. These findings demonstrate the potential of membrane distillation for simultaneous water reclamation and nutrient recovery in aquaculture wastewater treatment.

Nie et al. (2023) focused on the development of a composite functional particle-enhanced gravity-driven ceramic membrane bioreactor (GDCMBR) for the simultaneous removal of nitrogen and phosphorus from groundwater. The gravity-driven ceramic membrane bioreactor demonstrated efficient removal of ammonia nitrogen and phosphorus during a 60-day operation. The obtained effluent quality showed phosphorus levels below 0.05 mg/L and no detectable ammonia nitrogen. The ripening period for nitrogen and phosphorus removal was shortened to 10–15 days. The gravity-driven ceramic membrane bioreactor exhibited enhanced bacteria enrichment and sustained biological activity within the bioreactor. Nitrifying bacteria (*Nitrospira*) and denitrifying phosphorus-accumulating bacteria (*Exiguobacterium* and *Pseudomonas*) were present in the biofilter for nutrient removal. The gravity-driven ceramic membrane bioreactor flux dropped to 9.8 L/m^2.h due to microorganism accumulation on the membrane. The composite functional particle-enhanced gravity-driven ceramic membrane bioreactor demonstrated the potential to be an effective water treatment technology.

In one assessment considering the removal and recovery of phosphate, Anticó et al. (2021) developed a cellulose triacetate membrane via a double modification. The first modification step (surface medication) by Aliquat 366, while the second step (core modification) is by introducing nanoparticles into the matrix of cellulose triacetate. It was concluded that the removal of phosphate by magnetite-modified cellulose triacetate membrane attained 100%. Nonetheless, both silicon dioxide and titanium dioxide did not reveal a modification in the removal aptitude of phosphate. Also, Wang et al. (2016c)'s study elucidated the low affinity of the silicon dioxide-doped nanofiber membrane toward phosphate in which the adsorption capacity was 2.4 mg/g while adding zirconium acetate incremented the adsorption capacity of phosphate to 45.8 mg/g.

In another study, Karthikeyan et al. (2019) modified the chitosan membrane by lanthanum doping for the adsorptive removal of phosphate and nitrate. The experimental work indicated that the superb affinity of lanthanum-modified chitosan since maximal removal efficacy of nitrate and phosphate attained 62.6 and 76.6 mg/g, subsequently. These auspicious findings may be due to the powerful columbic interactions between the positive active species (lanthanum ion (La^{3+}), ammonium ion (NH_3^+), and hydronium ion (OH_2^+)) in an acidic medium and both anions. In addition to the possible ion exchange between chloride ions and the anions, which was confirmed by the energy-dispersive X-ray pattern that showed a significant decline in the chloride percentage after the adsorption processes. In this context, Xia et al. (2021) highlighted the improvement of porosity and hydrophilicity of polyvinylidene fluoride membrane by introducing lanthanum/carbon material. Based on the contact angle measurements, the hydrophilicity of lanthanum/carbon-embedded polyvinylidene fluoride was better than the pure membrane, suggesting an enhancement in the water flux of the modified membrane (Yang et al. 2007; Oh et al. 2009). Moreover, the pore size of pristine polyvinylidene fluoride and lanthanum/carbon-embedded polyvinylidene fluoride were in the range of 150–350 and 200–350 nm, respectively. Hence, the modified membrane exhibited superb % removal of phosphate with the finest antifouling ability.

Likewise, Yao et al. (2021) achieved high salt rejection by designing a polyester membrane utilizing a layer-by-layer polymerization technique. Noteworthy, such fabrication technique acquires the reverse osmosis membranes super high resistance toward chlorine species even in neutral or acidic medium. Contrariwise, conventional polyamide membranes, which are the premier manner in desalination, suffer poor durability during long exposure to chlorine. Consequently, the chlorine resistance of the designed polyester membrane was investigated in comparison with the commercial SW30 at varied pH conditions. The polyester membrane still with the same excellent stability at neural and acidic media even after exposure to 200 ppm for 500 h of chlorine species. While the membrane's performance slightly dwindled at an alkaline condition without changing its morphology. Conversely, the SW30 membrane deteriorated during an extremely short time since the water flux increased and the salt rejection diminished (Antony et al. 2010; Jimenez-Solomon et al. 2016; Huang et al. 2019).

In summary, several engineered membranes have shown suspicious results in removing nutrients from wastewater, even by adsorption or filtration. Especially, developing membranes by embedding metal–organic frameworks boosted the removal rate of nutrients and the recyclability of membranes.

Removal of pathogens

Indeed, disposing of harmful materials in wastewater grows enormous types of pathogens, such as viruses, bacteria, and so on. These organisms give rise to many health issues, including meningitis, polio, diarrhea, encephalitis, and hepatitis (Goswami and Pugazhenthi 2020). Notably, the separation of bothersome pathogens using membrane filtration technology, whether with pre-treatment or without, is a practical choice to overcome this actual hazard. In this context, numerous membrane configurations have been fabricated and developed. Among them, hollow polyvinylidene fluoride was utilized to separate coliphage MS2 from wastewater (Huang et al. 2012). The adsorption probability of viruses onto membranes may be the controlling factor in the virus's removal, even in the case of using a membrane with looser pores compared to the virus size. The experimental work revealed the fast adsorption of MS2 onto polyvinylidene fluoride during a filtration time of around 6–30 min, and the permeate throughput was 27 L/m^2. Also, Van Voorthuizen et al. (2001) separated MS2 using a polyvinylidene fluoride membrane but showed a higher permeate throughput attaining 1250 L/m^2.

In another study, Sundaran et al. (2019) designed a graphene oxide-incorporated polyurethane membrane for removing coliform from water bodies. It was concluded that the poor antibacterial activity of polyurethane membrane toward *Escherichia coli* and *Staphylococcus aureus*. Interestingly, the incorporation of graphene oxide into the membrane dramatically boosted the antibacterial action of polyurethane. This observation owes to the nanosheets of graphene oxide that could attach pathogens, as well as the direct contact mechanism and potent oxidative stress of graphene oxide. The contact between bacteria and the modified membrane resulted in the collapse of the bacterial cells and the leaking of the cytoplasm (Liu et al. 2018). The elevation in the graphene oxide amounts from 1 to 10% fostered the antibacterial action of the membrane from 70 to 90% for *S. aureus* and 95% for *E. coli*. The antibacterial membrane possesses many features in water remediation since it could prevent growing bacteria on the membrane's surface and also inhabit the biofilm formation, decreasing the fouling of the membrane (Zhu et al. 2018). Consequently, the antibacterial graphene oxide-incorporated polyurethane membrane has excellent antifouling and filtration characteristics.

Xu et al. (2012) fabricated an antibacterial membrane by immobilizing copper nanoparticles into a polyethyleneimine-deposed polyacrylonitrile membrane. The leaching amount of copper from the membrane was detected via atomic absorption spectrophotometric, showing the stability of copper ions since the leaching concentration was 1.13 mg/L in ethylenediaminetetraacetic acid solution during the first 4 h, then after no leaching was observed. More importantly, the antibacterial efficacy of the copper-doped membrane and the neat membrane against *E. coli* was 71.5% and 14.5%, respectively. Also, copper-doped chitosan/polyethylene oxide/TEMPO-oxidized cellulose membrane exhibited a favorable bacterial removal rate of about 100% against *E. coli* and *Bacillus subtilis* (Bates et al. 2021). In addition to the excellent bactericidal property of the copper-embedded membrane attained 1.98% for *E. coli* and 25.57% for *B. subtilis*, as well as its auspicious bacteriostatic property where the diameter inhibition zone in the case of *E. coli* was 2.9 mm and 6.5 mm in the case of *B. subtilis*.

Szczuka et al. (2020) evaluated the effectiveness of forward osmosis-reverse osmosis (FO-RO) hybrid systems in removing pathogens from challenging water sources, such as reverse osmosis concentrate, graywater, and filtered sewage, for centralized and decentralized potable reuse applications. The study found that forward osmosis-reverse osmosis treatment achieved high removal rates of pathogens. In the case of bacteriophage MS2, a surrogate for viruses, forward osmosis-reverse osmosis treatment achieved a removal rate of $\geq 6.7 - \log$ when spiked into graywater and sewage. Native *E. coli* in graywater and sewage was also effectively removed, with $\geq 5.4 - \log$ and $7.9 - \log$ removal, respectively. However, it was noted that the detection of MS2 and *E. coli* in the forward osmosis-reverse osmosis permeates indicated the need for additional disinfection. Despite the high rejection of pathogens, the study suggested that additional disinfection steps should be implemented to ensure complete pathogen removal.

In another research study, Pazouki et al. (2022) investigated the efficacy of two low-energy dilution desalination processes, namely osmotic dilution desalination and mixing dilution desalination, in removing pathogens from seawater. The study used real seawater and recycled wastewater as influent sources and assessed the removal efficacy of bacterial indicators (*Clostridium perfringens* and *E. coli*), coliphage genera *Microviridae*, and *Human adenovirus* (HAdV) in each membrane configuration. The results showed that both forward osmosis and ultrafiltration membranes were effective in removing viruses, with the forward osmosis membrane achieving a removal rate of 5.1 $\log_{10}$ and the ultrafiltration membrane achieving 4.1 $\log_{10}$ removal. Additionally, no trace of bacterial indicators was found in the reverse osmosis permeate from either the forward osmosis-reverse osmosis or ultrafiltration-reverse osmosis configurations. Comparing the two membrane configurations, the forward osmosis membrane demonstrated slightly better pathogen log removal values (LRVs) than the ultrafiltration membrane. The forward osmosis membrane achieved a 5.0 LRV for viruses and a 4.2 LRV for bacterial indicators, while the ultrafiltration membrane achieved LRVs of 3.7 and 3.6 for viruses and bacterial indicators, respectively. The study also found that dilution desalination, through both osmotic dilution desalination and mixing dilution desalination processes, resulted in a reduction in the concentration of organic pathogen contaminants in the influent feed waters. Moreover, most bacterial indicators detected in the reverse osmosis permeate were nonpathogenic strains, as indicated by comparative 16S rRNA sequencing.

Overall, this research demonstrates that hybrid forward osmosis-reverse osmosis or ultrafiltration-reverse osmosis processes can effectively remove pathogens from seawater, with the forward osmosis membrane showing slightly better performance in pathogen removal compared to the ultrafiltration membrane. These findings contribute to the understanding of pathogen removal efficacy in seawater dilution desalination processes, which is crucial for ensuring the safety of water reuse and addressing water scarcity challenges.

Olivares Moreno and Altintas (2022) developed a highly efficient membrane system for the removal of waterborne pathogens, with a specific focus on the removal of adenoviruses. Adenoviruses are particularly challenging to eliminate from water sources due to their resistance to common purification methods such as ultraviolet irradiation and chlorination. The study successfully addressed this challenge by creating a bioselective polyethersulfone (PES) membrane through a combination of chitosan hydrophilic surface modification and the immobilization of adenovirus-specific molecularly imprinted nanoparticles (nanoMIPs). The membrane demonstrated excellent virus removal capabilities, successfully separating 99.99% of the viruses from the water samples. This high removal efficiency was achieved by the specific binding of the adenoviruses to the immobilized nanoMIPs on the membrane surface.

Cordier et al. (2020) focused on the removal of pathogens from seawater using ultrafiltration, with a specific emphasis on shellfish production. The study targeted two pathogens: *Vibrio aestuarianus* and Ostreid herpesvirus 1 (OsHV-1). The objective was to produce high-quality water for shellfish production by evaluating the retention of these microorganisms through ultrafiltration. The results showed that ultrafiltration was effective in removing the targeted pathogens. For OsHV-1, in vivo experiments using oyster spat and larvae, which are highly susceptible to the virus, validated the protection of oysters. Oysters raised in contaminated seawater that were subsequently treated by ultrafiltration showed similar mortality rates to the negative controls. Regarding *Vibrio aestuarianus*, ultrafiltration achieved a high retention of the bacteria in seawater, with concentrations below the detection limits of the analytical methods used. The quantity of *Vibrio aestuarianus* was at least 400 times lower than the threshold known to induce mortalities in oysters. Industrial-scale experiments over several months further confirmed the retention of *Vibrio* bacteria. The study also demonstrated the stability of the ultrafiltration process over time, even in the presence of algal blooms. These findings have implications for the improvement of water quality in aquaculture and the prevention of diseases that can affect shellfish populations. Thus, ultrafiltration is a validated method for the treatment of seawater, effectively removing targeted pathogenic microorganisms and contributing to the biosecurity of shellfish production.

Accordingly, excessive assessments have been performed to engineer membranes with outstanding antimicrobial action and filtration properties. Antimicrobial membranes imply a promising removal rate for many pathogens. Notably, doping excellent antibacterial materials, like graphene oxide, copper, etc., in the membrane matrix enhanced the antibacterial action of some polymeric membranes.

Gas separation

Gas separation from gas/vapor mixture is a requisite process to fulfill the specific requirements of a product with high quality (Abetz et al. 2006). For this purpose, diverse conventional separation approaches have been applied, such as evaporation, drying, distillation, and absorption. Nonetheless, these separation ways consume excessive energy, reaching about 10–15% of the total consumed world's energy (Sholl and Lively 2016). Some of these strategies, like adsorption-absorption and cryogenic distillation, are not energy-consuming, but they generate high pollution (Baker 2002). Membrane technology has revealed advantageous features in separating gas/vapor mixtures, including eco-friendly merit, facile scale-up and operation, small footprint, cost competitiveness, and modularity (Baker 2012, Peng et al. 2012). Additionally, gas separation by membrane process consumes merely 90% of the traditional approaches to gas separation (Sholl and Lively 2016).

Carbon dioxide separation

Carbon dioxide's capture from fuel and combustion flue gases is an imperative requirement for alleviating the inevitable economic and environmental effects of carbon dioxide on climate change. Separation of carbon dioxide via membrane strategy surpasses the other ways, such as physical and chemical absorption processes, owe to operational ease, low depleted energy, and outdoing the limitations of thermodynamics solubility. Noteworthy, membranes acquire vast consideration in stationary power applications since they could be applied in the stream processing during oxo-combustion, pre-, and post-combustion, separating oxygen/nitrogen, carbon dioxide/hydrogen, and carbon dioxide/nitrogen gas pairs, respectively (Alivisatos and Buchanan 2010; Merkel et al. 2010). During the post-combustion, the used membrane is designed downstream of the combustion to separate the lower-pressure carbon dioxide from nitrogen. The higher-pressure carbon dioxide is separated from syngas via pre-combustion. For producing highly pure oxygen, oxo-combustion is applied and ultimately generates the water stream and carbon dioxide with high concentrations, which would be compressed and dehydrated (Valappil et al. 2021). Hence, designing membranes with high carbon dioxide permeability is an essential target for large-scale separation processes. In this context, Duan et al. (2019a) engineered a Covalent organic framework (COF-5)-embedded Perbax-1657 membrane for enhanced carbon dioxide permeability. It was observed that the optimal COF-5 proportion into the membrane was about 0.4 weight percentage since the permeability of carbon dioxide attained 493 Barrer (1 Barrer = 10^{-10} cm^3 (STP) cm/(cm^2 s cmHg)). Furthermore, the super high affinity of ether in poly ethylene oxide toward carbon dioxide, results in a high carbon dioxide permeability using poly ethylene oxide-based membrane (Lin and Freeman 2005). For instance, high carbon dioxide permeability attained 750 Barrer using poly ethylene oxide-ran-propylene oxide (Lin and Freeman 2004), while in the case of neat poly ethylene oxide (Reijerkerk et al. 2010), the permeability was about 12 Barrer.

Oxygen separation

To date, the production of oxygen via membrane technology needs further developments due to the almost similar diameter of nitrogen (3.64 A) and oxygen (3.46), rendering the separation based on size using polymeric membranes unsuitable (Robeson 2008). Moreover, the purity of the produced oxygen via membrane separation strategy is incomparable to the super-high pure oxygen that is generated by conventional approaches (Dong et al. 2013). Accordingly, sustained investigations have been accomplished to boost air separation by membranes. In one of these investigations, Prajapati et al. (2019) deduced that the doping of 1 weight percentage of zeolite into 4A poly dimethylsiloxane elevated the oxygen permeability from 438 to 477 Barrer to 564–654 Barrer at pressure 100 and 250 kPa, respectively. In addition, over-increasing the embedded zeolite to 5 and 10 weight percentages boosted the oxygen permeability 2- and 15-fold of the pure membrane, respectively. In another study, Daglar et al. (2021) fabricated varied metal–organic frameworks-decorated polymeric membranes for air separation. The experimental works exhibited the oxygen/nitrogen selectivity of MIL-101, Cu-BTC, MOF-5, MIL-53, ZIF-67, UiO-66, and ZIF-8 was in the range of 5.4–22.2, while their oxygen permeability was between 4.1×10^4 and 5×10^5 Barrer. Despite these auspicious results, the metal–organic framework membranes suffer reproductivity and incomplete membrane/support intergrowth, agreeing with Venna and Carreon (2015). Thence, metal–organic frameworks were used as fillers to foster the gas separation efficiency of pristine polymers that have pretty low oxygen permeability and selectivity (Murali et al. 2013). Surprisingly, the maximal oxygen/nitrogen selectivity of the metal–organic framework/polymer membrane was about 19.8, and the oxygen permeability attained 2710.8 Barrer.

Hydrogen separation

Currently, numerous hydrogen recovery approaches are immensely exploited, comprising pressure swing adsorption, cryogenic distillation, and membranes (Perry et al. 2008; Thomassen et al. 2010). Notably, the membrane strategy is better than other approaches for separating hydrogen from a gas mixture due to its energy saving and high purity of the yielded hydrogen (Thomassen et al. 2010). Additionally, both pressure swing adsorption and cryogenic distillation demand doubled unit and supplemental wash column for eliminating the attached carbon mono/dioxides (Perry et al. 2008). The membrane separation strategy works by permeating the hydrogen gas through the membrane, keeping the other gases mixture in the feed. Nonetheless, such a process needs the recompression of hydrogen for transportation and utilization. Thence, the membrane separation requires further equipment, energy, and cost. Accordingly, researchers have endeavored to scrutinize membranes to retain the smaller molecules of hydrogen gas and pass the larger molecules, which dissolves the recompression drawback of the membrane (Dong et al. 2013). Although sustained investigations have been performed to enhance the permeance and selectivity of membranes, most of these research studies are suitable only for lab-scale (Choi et al. 2010). Hence, it is urgent to develop the permselectivity and mechanical properties of membranes for efficient hydrogen separation.

In one attempt, Zhang and Koros (2017) focused on improving the permselectivity of the membrane by incrementing the carbonization temperature. It was noticed that a dramatic enhancement in the selectivity from 3 to 11, corresponding to elevating the carbonization temperature from 750 to 900 °C, respectively. Nevertheless, the hydrogen permeability drastically dwindled from 1600 to 240 Barrer. Hence, a larger membrane area is required to overcome this gas permeance reduction, which increases the operational cost more than the saved cost by raising the permselectivity of the membrane. Furthermore, Lei et al. (2021) fabricated a carbon membrane for the selective separation of hydrogen from the carbon dioxide/hydrogen gas mixture. The experimental results exhibited the promising separation property of the as-prepared carbon membrane where the hydrogen permeance reached 111 units, with a selectivity of about 36.9 at 110 °C and 10 bar. More importantly, the membrane revealed excellent stability in the existence of humidified gas at a pressure of 14 bar and temperature of 90 °C.

In conclusion, the membrane separation strategy possesses promising merits, surpassing other gas separation methods owes to its eco-friendly, easy operation, modularity, cost competitiveness, energy saving, and small footprint. The developed membranes exhibited outstanding separation performances toward many gases, such as hydrogen, oxygen, and carbon dioxide, as elucidated in

Table 7 Separation performances of various developed membranes for different gases. Permeability values in Barrer are provided, offering insights into the diverse applications of these membranes in gas separation, including carbon dioxide, oxygen, and hydrogen, demonstrating their selectivity and effectiveness. 1 Barrer = 10^{-10} cm^3 (STP) cm/(cm^2 s cmHg)

Membrane	Type of gas	Permeability (Barrer)	References
PEO	Carbon dioxide	12	Lin and Freeman (2004)
PEO-*ran*-PPO	Carbon dioxide	470	Reijerkerk et al. (2010)
Pebax/zeolite Y	Carbon dioxide	940	Chen et al. (2015)
PEG-DBE	Carbon dioxide	750	Yave et al. (2010)
COF-5/Pebax	Carbon dioxide	493	Duan et al. (2019b)
Pebax1074/PEG	Carbon dioxide	528	Feng et al. (2013)
Matrimid/MOF-5	Carbon dioxide	20.20	Perez et al. (2009)
PEO-PBT	Carbon dioxide	400	Yave et al. (2010)
Zeolite 4A-PDMS	Oxygen	6700–7200	Prajapati et al. (2019)
MOF/polymer MMMs	Oxygen	2710.8	Daglar et al. (2021)
DFTTB	Oxygen	137	Ma et al. (2021)
BO-based polymer	Oxygen	15	Lee et al. (2013)
Cobalt-based ionic liquid/PIM-1	Oxygen	140	Zhao et al. (2023a)
siloxane modified PI	Oxygen	1.35	Boroglu and Gurkaynak (2011)
PSF-PEO	Oxygen	0.4	Kim and Park (2011)
POC	Hydrogen	266	Song et al. (2016)
CMT	Hydrogen	28,280	Liu et al. (2020b)
PIM-EA-TB	Hydrogen	7760	Carta et al. (2013)
Carbon/carbon mixed matrix	Hydrogen	1600	Lei et al. (2021)
6FDA-durene PI	Hydrogen	593.1	Lin and Chung (2001)
PDMS	Hydrogen	950	Merkel et al. (2001)
PTMSP	Hydrogen	11,800	
Co-PI	Hydrogen	5.29	Choi et al. (2010)

Abbreviated expressions: PEO: polyethylene oxide, PEO-*ran*-PPO: polyethylene oxide-ran-propylene oxide, PEG-DBE: polyethylene glycol-dibutyl ether, COF: covalent organic frameworks, MOF: metal–organic framework, PEO-PBT: polyethylene oxide-polybutylene terephthalate, MOF/polymer MMMs: metal–organic framework /polymer mixed matrix membranes, DFTTB: obtained by the design of a 2,3-difluoro-functionalized triptycene (DFTrip) building block, BO: Benzoxazole, PIM: polymer of intrinsic microporosity, PI: polyimide, PSF-PEO: polysulfone–polyethylene oxide, POC: porous Organic Cage, CMT: conjugated microporous thermoset, PIM-EA-TB: polymers of intrinsic microporosity-ethanoanthracene-Tröger's base, 6FDA-durene PI: polyimide was synthesized from 2,2-bis(3,4-dicarboxyphenyl)hexafluoropropane dianhydride, and PTMSP: poly(1-trimethylsilyl-1-propyne)

Table 7. Recently developed polymeric membranes for gas separation. Comparison between the gas permeability of various polymeric membranes. Recent studies deduced that the high carbon dioxide permeability using polymeric membranes reached about 1000 Barrers. In addition, excellent oxygen separation using membrane technology. Hydrogen separation via membrane strategy demonstrated outstanding results compared to other methods.

Energy applications

Sustaining life on our planet mainly relies on the presence of sufficient energy. Especially the recent situation of climate change and the ozone layer imposes finding clean modes for energy production instead of the common fossil commodities. There has been an obvious decline in the use of fossil fuels in the past few years; nevertheless, it is still the vastest energy generation form. Overmuch attempts from scientists around the world to find eco-friendly alternatives to fossil fuel because of its certain jeopardies on human health that were scientifically confirmed. In addition to the unstable prices of fossil fuel, it causes economic crises in the countries. Interestingly, some alternatives have been shined lately owing to their efficacy and eco-friendly merits, as will be explained in the following.

Fuel cell

Amongst the propitious alternative energy modes are fuel cells, which have acquired attention due to their high efficiency in energy generation/storage with zero pollution since it does not emit the common contaminants of fossil fuel (Qiu et al. 2019). Nonetheless, the high cost of the used materials in fuel cells and the expensive operation cost hinder the applicability of fuel cells (Ogungbemi et al. 2019). Generally, fuel cells are classified based on their size and structure, polymer electrolyte membrane properties, and operative environment. The fuel cell modes are categorized into proton

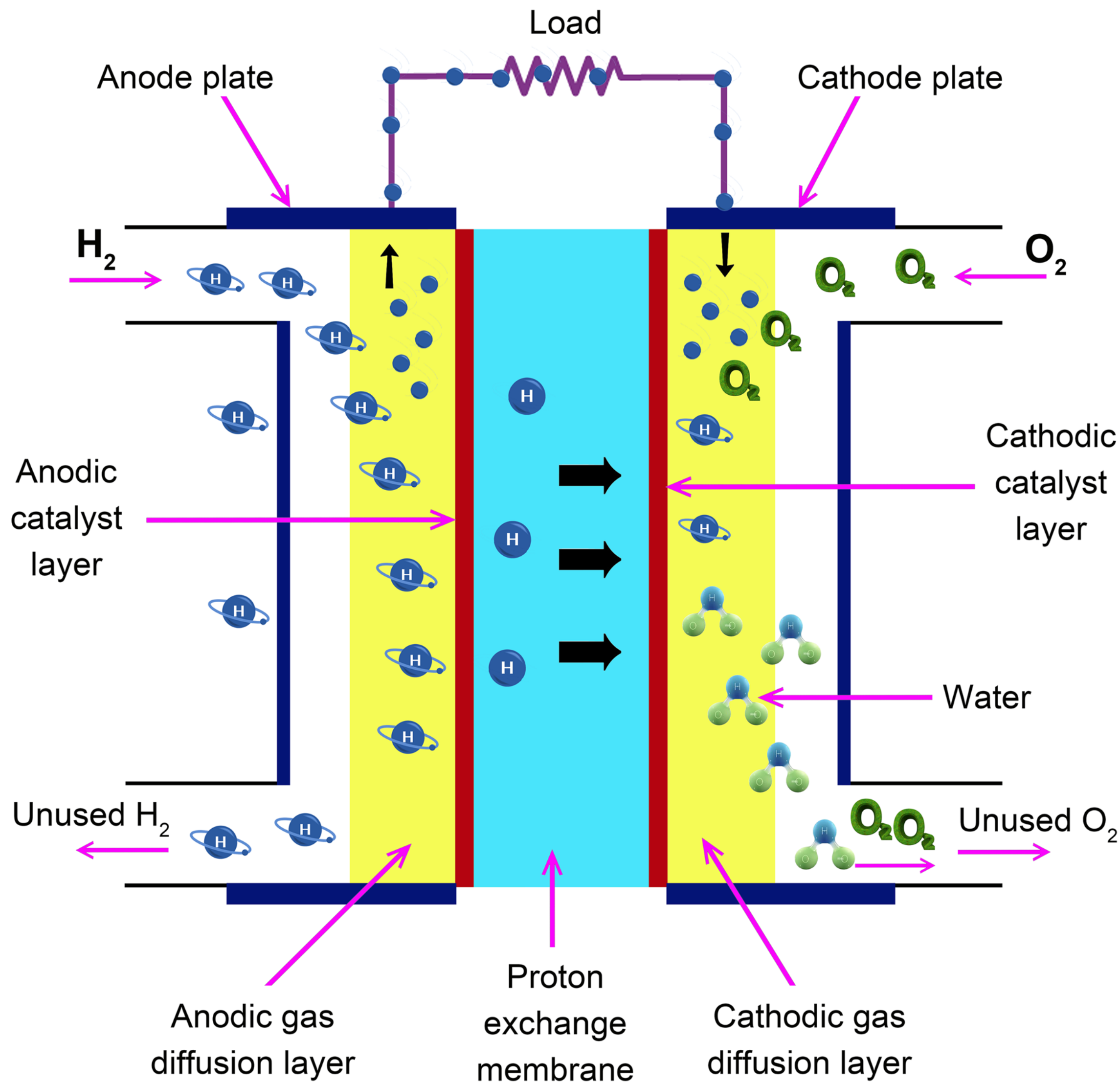

Fig. 7 Proton exchange membrane fuel cell diagram. This figure provides a visual depiction of the internal workings of a proton exchange membrane fuel cell (PEMFC). The schematic illustrates the flow of reactant and product gases within the cell, as well as the direction of ion conduction. In the PEMFC, hydrogen (H_2) is supplied as the fuel, and oxygen (O_2) as the oxidant. The hydrogen gas is split into protons (H^+) and electrons (e^-) at the anode, with the protons passing through the proton exchange membrane. Meanwhile, the electrons travel through an external circuit, generating an electric current. At the cathode, the protons and electrons combine with oxygen to produce water (H_2O) as the main product. This schematic highlights the essential processes and directional flow of ions and gases in a PEMFC

exchange membrane, direct alcohol, anion exchange membrane, molten carbonate, solid oxide, phosphoric acid, and proton exchange membrane fuel cells (PEMFCs) (Hashim et al. 2009). Significant attention has been drawn toward PEMFCs, renowned for their remarkable hydrogen energy efficiency, captivating the interest of numerous experts, as illustrated in Fig. 7 (Li et al. 2023a, b). In recent times, substantial advancements have been achieved in this domain. PEMFCs are regarded as exemplary energy storage devices due to their superior operational features and absence of pollution, setting them apart from conventional fuel cells (Ding et al. 2023). However, the former is favorable owing to its superb efficacy, as well as the fact that it does not generate emissions or pollutants. Furthermore, the proton exchange membrane is primarily exploited in electrical energy production via chemical reactions (Wilson et al. 2013). The system composition of the fuel cell is constructed from; a polymeric electrolyte membrane, gas diffusion layer, and catalyst layer (Casalegno et al. 2007; Chang et al. 2008) in addition to the centered proton electrolyte membrane in the middle of the fuel cell that is responsible for the proton transfer, the flow of electrons and fuel, and the conservation of mechanical and chemical stability (Heinzel and Barragan 1999). Hence, for the importance of proton electrolyte membrane, many studies have boosted it to increase its oxidative stability, proton conductivity, and mechanical/thermal stability, as well as decline the process cost and fuel crossover (Peighambardoust et al. 2010; Shaari and Kamarudin 2019).

In one study, Lee et al. (2019) designed sulfonated polyarylene ether sulfone/sulfonated poly arylene thioether sulfone-grafted graphene oxide membranes (SPAES/SPA-ES/GO) as a filler for PEMFC. Interestingly, it was monitored for an enhancement in the tensile strength of the pure SPAES after adding SPA-ES/GO. This observation may be accredited to the possible interactions between sulfonic acid-containing SPAES and the belonging functional groups of graphene oxide, in addition to the π-π interactions between SPAES and graphene oxide. The acquired results of the proton conductivity test denoted an increase in the membranes' conductivity with the increase in their relative humidity, which may be attributed to increasing the water content that could be a proton carrier and also a bridge between the abundant sulfonic functional groups (Yang et al. 2008). The optimal graphene oxide concentration in the SPAES/SPA-ES/GO membranes was 2 wt.% since the proton conductivity attained 131.43 mS/cm. The neat SPAES membrane revealed a higher proton conductivity value than the SPAES/SPA-ES/2 (wt.%) GO at a relative humidity lower than 80%; however, SPAES/SPA-ES/2 (wt.%) GO possesses higher water uptake owing to the presence of the hydrophilic graphene oxide. Also, Yang et al. (2022) exhibited an auspicious enhancement in the proton conductivity of the sulfonated polyimide membrane after introducing MIL-101(Fe)-NH_2 reached 0.194 S/cm. This finding owes to the individual structure of MIL-101(Fe), the synergistic effect of the additional amino groups, and the acid–base interactions that increase the proton conduction.

In another study, Nayak et al. (2023) fabricated a membrane from sulfonated poly ether-ether-ketone, silicon dioxide, and polyvinylidene fluorideco-hexafluoro propylene for a microbial fuel cell. The microbial fuel cell's performance relies on the metabolism and the growth of anaerobic bacteria that may be hindered when oxygen diffuses from the cathode, passing through the membrane to the anode. Notably, the elevation in the embedded silicon dioxide proportion from 2.5 to 10 weight percentage improved the oxygen permeation declined from 8.3×10^{-7} to 8.8×10^{-8} cm^2/S. In addition, sulfonic acid groups act as oxygen barriers, which boost the oxygen permeability resistance of the membrane as well.

Biodiesel separation

Biodiesel is a clean, renewable, and biodegradable energy source, which is distinguished by its non-toxic emitted gases as it does not contain sulfur or organic substitutes (Demirbas 2009; Guldhe et al. 2015). In general, biodiesel production proceeds via the oil/alcohol transesterification process in the existence of a catalyst (Endalew et al. 2011). Nonetheless, the feedstock may contain fatty acids and water, giving rise to the form of soap that dramatically deactivates the used catalyst and directly renders the bio-diesel separation pretty hard (Chen et al. 2014; Yadav et al. 2017). It is well known that biodiesel economics is mainly determined based on its purity degree. Consequently, diverse technologies are utilized to separate the biodiesel, including membrane, gas stripping, extraction, pretraction, and adsorption (Hajilary et al. 2019). Membrane technology is deemed cost-effective and more efficient than the other strategies owing to its superb selectivity, relatively high efficacy, operational simplicity, ease of control, energy saving, high stability under varied conditions, eco-friendliness, and scale-up (Atadashi et al. 2011). Hence, several assessments were executed to foster the efficiency of membranes in the bio-diesel separation and study the impact of the various operational conditions on the quality of the separated biodiesel.

In one assessment, Bansod et al. (2022) engineered silicon dioxide/aluminum oxide ceramics membranes with varied pore sizes for separating glycerol from biodiesel. The glycerol retention reached 99.8% at a pressure of about 3 bar, 10 (wt.%) of ethanol, and using a ceramic membrane with a pore size of 0.2 mm. The ethanol concentration influenced the glycerol retention since the optimal glycerol retention was 99.8% using 10 wt.% of ethanol. At the same time, the raising in the ethanol concentration over 10 wt.% declined the retention of glycerol. This performance may be due to the ability of ethanol to act as a surfactant in which its polar part attaches to glycerol, and the nonpolar interacts with the biodiesel, decreasing the glycerol/biodiesel interfacial tension. Thus, the glycerol molecules are easily collapsed into smaller droplets and penetrate through the membrane, increasing the glycerol concentration in permeate flux and directly dwindling the glycerol retention (Pittia et al. 2005; Lin and Lin 2007). In this context, Gomes et al. (2010) deduced that the best glycerol retention was around 99.6% by a 0.2 µm pore size ceramics membrane at 2 bar and 5 wt.% of ethanol. Likewise, the over-raising in the ethanol concentration over 5 wt.% led to an increase in the glycerol in the permeate flux reached the maximum level (0.19 ± 0.013% mass) using 20 wt.% ethanol.

Furthermore, Saleh et al. (2010) fabricated a developed polyacrylonitrile membrane for separating glycerol from fatty acid methyl esters (FAME). The impact of the present materials on the transesterification process, such as water, methanol, and soap, on the glycerol separation was investigated. The experimental findings implied the purification of FAME from glycerol using the as-fabricated membrane, reaching the standards of EN 14214 and ASTM D6751. A small proportion of water (2 g water/1 L FAME) is required to form large glycerol particles in FAME and facilitate the glycerol separation. In addition, the presence of 1% methanol had a negative result on the glycerol separation from FAME, while 1% soap almost prevented the glycerol separation.

Purification of biogas

Biogas production essentially proceeds via the anaerobic digestion of organic wastes, wastewater remediation plants, and gas recovery from landfills (Ryckebosch et al. 2011; Baena-Moreno et al. 2019a). Generally, biogas mainly consists of nitrogen, carbon dioxide, and methane gases. In addition to the possible existence of ammonia, water vapor, hydrogen sulfide, or oxygen, according to the feed source and locations, climate conditions, and the adopted technology (Awe et al. 2017). The hydrogen sulfide traces in biogas cause many problems, especially in the existence of water vapor where they react and generate sulfuric acid and hydrogen that decline the calorific value of biogas and corrode the machine's pipes (Baena-Moreno et al. 2019b). Moreover, carbon dioxide is the biggest problem in producing purified biogas since it diminishes the calorific value and over-raises the compression and transportation costs (Rosha et al. 2021). It is critical to remove these impurities to produce purified biogas, which has high-quality methane gas that can be employed in wide applications: heat production, vehicle fuel, fuel cells, and electricity (Farghali et al. 2022). For purifying biogas from carbon dioxide, varied technologies have been applied, comprising water scrubbing, cryogenic separation, chemical absorption, biological method, and pressure swing adsorption (Liu et al. 2022). In addition, membrane separation is more desirable than the former technologies owing to its high energy efficiency, high selectivity (about 97%), excellent efficacy in methane recovery, and operation simplicity (Basu et al. 2010; Franco et al. 2021). Nonetheless, membrane separation has drawbacks, such as selectivity/permeability tradeoffs, high cost of membrane production, and membrane. Thereby, continued research investigations have been done day-by-day to boost the efficiency and lifetime of membranes and diminish their production capital cost.

In this context, Yang et al. (2019a) fabricated a Pebax-embedded amino organosilicon nanotube membrane for methane purification from carbon dioxide. The results showed the positive role of the amino group in the carbon dioxide/methane selectivity from 25 to 29 because of its ability to transport carbon dioxide. Furthermore, the membrane's porosity and the introduced amino group vastly enhanced the permeability of carbon dioxide from 9000 to 9500 Barrers throughout the membrane. In addition, the absorption stability of polytetrafluoroethylene membrane was examined in the separation of carbon dioxide throughout 36 h. It was observed that the removal of carbon dioxide exceeded 99%, and the flux was still about 0.72×10^{-3} mol/m^2.s (Li et al. 2021). Such promising stability may be due to the hydrophobic character of the membrane. Notably, Nishikawa et al. (1995) inferred the polytetrafluoroethylene stability during the carbon dioxide absorption for 6600 h.

Furthermore, Zito et al. (2022) designed a polyetherimide/polyimide membrane for methane purification. The carbon dioxide/methane selectivity was 17.4 in mixed gas conditions, while the selectivity diminished to 16.6 in a wet condition due to the water vapor existence. Interestingly, exposing the polyetherimide/polyimide membrane to water vapor and hydrogen sulfide declined the carbon dioxide permeability by only 14% after 646 days.

In terms of biogas slurry, reverse osmosis membranes have also been applied in the concentration of biogas slurry. In one instance, an integrated sand filter/microfiltration/ultrafiltration/reverse osmosis process was used to concentrate biogas slurry for fertilizer and water recovery. The pilot test demonstrated that reverse osmosis membranes achieved high chemical oxygen demand and ammonia nitrogen removal rates, and fouling issues were addressed using optimized chemical agents (Ruan et al. 2015). Furthermore, reverse osmosis membranes offer versatile solutions for simultaneous gas removal. Dolejš et al. (2014) explored the use of thin film composite-polyamide membranes to simultaneously remove carbon dioxide and hydrogen sulfide from agro-biogas. The thin film composite membrane, in its water-swollen state, exhibited the ability to remove carbon dioxide and sulfur oxide up to 82% and 77%, respectively, at 220 kPa. The advantage of this process is that it eliminates the need for pre-treatment to remove water vapor, which can negatively impact the performance of other membranes.

In summary, membrane separation technology revealed propitious performance in providing alternative clean energy like fuel cells, biogas, and biodiesel. Its efficacy and eco-friendly advantages characterize membrane technology. However, the durability and cost of membranes still require further investigation.

Other applications

Reverse osmosis has been employed in various applications, where previously reported reverse osmosis applications in concentrating juice. The interest in reverse osmosis concentration of fruit juices began 40 years ago, owing to its benefits over conventional thermal-based processes: (i) minimal thermal component damage, (ii) low energy consumption, and (iii) capacity to create high-quality goods (retain product taste) (Wenten and Khoiruddin 2016). Table 8 shows the performance of the reverse osmosis membrane during the concentration of various juices.

In this context, Bagci et al. (2019) discovered that the concentration of pomegranate juice can be increased fourfold, from 15.6 to 65 °Brix, by combining reverse osmosis and osmotic distillation processes with enhanced performance. The researchers utilized a low-pressure nitrogen plasma

Table 8 Reverse osmosis membrane performance in juice concentration. The initial and final concentrations in °Brix, along with the membrane type and operating conditions (pressure and temperature), are detailed. These diverse applications showcase the efficacy of different reverse osmosis membrane configurations in concentrating juices, providing valuable insights for fruit processing industries

Juice	Initial concentration (°Brix)	Membrane	Operating conditions		Final concentration (°Brix)	References
			Pressure (bar)	Temperature (°C)		
Carrot	5	Spiral wound polyamide	25	20	13.6	Cassano et al. (2003)
Blackcurrant	16.5	Tubular polyamide membrane	60	25	28.6	Pap et al. (2009)
Apple	11	Tubular polyamide membrane	55	35	26	Alvarez et al. (1997)
Camu-camu	6	Plate-and-frame thin film composite	60	22	25.5	Rodrigues et al. (2004)
Acerola	7.1	Plate-and-frame thin film composite	60	25	29.2	Matta et al. (2004)
Grape	14.7	Plate-and-frame thin film composite	60	40	28.2	Gurak et al. (2010)
Orange	8	Plate-and-frame polyamide membrane	60	25	36	Jesus et al. (2007)
Pear	11.9	Polyamide membrane (pilot plant)	40	25–27	28.9	Echavarría et al. (2012)
Peach	10.9	Polyamide membrane (pilot plant)	40	25–27	30.5	Echavarría et al. (2012)
Pomegranate	15.6	LPNP-modified PSF/PA TFC, fat sheet	40	25 ± 1	65	Bagci et al. (2019), Sarbatly et al. (2023)
Nagpur Mandarin	9	Spiral wound polyamide	Not mentioned	10.4	60.4	Kumar et al. (2020), Sarbatly et al. (2023)

Abbreviated expressions: LPNM: low-pressure nitrogen plasma, PSF: polysulfone, PA: polyamide, and TFC: thin film composite

(LPNM)-modified commercial thin-film composite membrane in the reverse osmosis process as a pre-concentration step before further concentration with osmotic distillation. The LPNM-modified reverse osmosis membrane's performance was compared to that of a standard commercial reverse osmosis membrane. Although there was no significant difference in the operating time required to achieve a concentration of 65 °Brix when using the commercial reverse osmosis membrane with osmotic distillation process compared to standalone osmotic distillation concentration, the LPNM-modified commercial reverse osmosis membrane exhibited excellent performance when combined with osmotic distillation. It reduced the duration of the concentration process by 36% while preserving the aroma of the juice, which is typically lost when osmotic distillation is used alone. The chemical content of the juice remained well-preserved. However, due to increased membrane permeability resulting from LPNM modification, the retention of malic acid, gallic acid, glucose, and fructose was lower compared to osmotic distillation and commercial reverse osmosis-osmotic distillation concentration processes.

In another study, Kumar et al. (2020) investigated the potential of hybrid membrane processes involving reverse osmosis and osmotic distillation for concentrating mandarin juice. They preconcentrated clarified Nagpur mandarin juice using a polyamide spiral-wound reverse osmosis membrane at a low temperature of 10.4 °C. As shown in Table 8, the reverse osmosis retentate was then further concentrated using a polypropylene hollow fiber osmotic distillation process at 25.4 °C, with a calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) solution (at a weight ratio of 2 draw solutions to 1 feed solution). After 16 h of operation, the final concentration of clarified Nagpur mandarin reached 60.4 °Brix, corresponding to a 6.7-fold concentration factor.

Similarly, in drying milk, reverse osmosis is employed for concentrating milk by taking advantage of low working temperatures. The pre-concentration of milk can help in diminishing transportation costs (Deshwal et al. 2021). Mainly, reverse osmosis is applied in the dairy field to recover milk lactose and proteins, along with generating a permeate that can be reused for cooling or rinsing, Spiral wound modules have been utilized extensively due to their high availability and efficient cost (Wang and Wang 2019). Moreover, the concentration of milk leads to manufacturing ice cream by reverse osmosis as water content that can be eliminated reaches 70% while solids can be maintained (Wenten and Khoiruddin 2016).

Nanofiltration membranes are utilized in the dairy industry to allow the passage of unwanted monovalent ions like sodium, potassium, and chlorine for the demineralization of whey products and concurrently working on raising the concentration of constituents such as calcium, protein, and lactose (Rice et al. 2005). Also, nanofiltration can be employed in the separation of various neutral species, such as simple monosaccharides glucose (180 MW) and xylose (150 MW) (Sjöman et al. 2007).

In the pharmaceutical industry, nanofiltration enables the separation and purification of pharmaceutical compounds, concentration of active ingredients, and removal of impurities from synthesis reactions. It offers a reliable solution for meeting stringent quality standards and regulatory requirements (Mallakpour and Azadi 2021; Yadav et al. 2022). Furthermore, in metal plating and electronic industries, nanofiltration plays a crucial role in the recovery of metal salts and purification of process streams (Wei et al. 2013; Basaran et al. 2016). Other industries, such as agriculture (Zacharof et al. 2016) and natural essential oils (Donelian et al. 2016), benefit from nanofiltration. It aids in the removal of contaminants, fractionation of compounds, and concentration of valuable components. Nanofiltration contributes to resource efficiency, waste minimization, and the production of high-quality products. Table 9 summarizes key industrial processes in which nanofiltration is utilized as a primary or in conjunction with other separation techniques (Nath et al. 2018; Du et al. 2022).

Pervaporation is a new technique for gasoline desulfurization that gained much interest owing to the auspicious ability to remove eco-friendly sulfur in the petrochemical industry due to the significant pervaporation characteristics such as feasibility, economical, and highly selective membranes. Fluid catalytic cracking gasoline encompasses 85–95% of sulfur elements besides 30–40% of the overall gasoline (Wang et al. 2020a). Thus, desulfurization from fluid catalytic cracking is a vital step to attain extreme desulfurization of gasoline.

Hou et al. (2019) enhanced pervaporation membrane performance by incorporating silica nanoparticles into polyvinyl butyral, and for tackling membrane defects, a coupling agent was added to improve the compatibility among polyvinyl butyral and silica. When operating under higher temperatures, the gasoline rate diffusion across the membranes is elevated, therefore accompanied by elevating permeation flux. Considering the ideal operating temperature is 80 °C, the flux attains 1.44 $kg/m^2.h$ with 2 wt.% silica to polyvinyl butyral mass ratio. While in the medical field, pervaporation was conducted by Slater et al. (2012) to act as a green drying method for recovering tetrahydrofuran in drug preparations. Moreover, this study has been utilized in the preparation of a novel tumor drug step.

Conclusion

The global challenges of sustainable development, environmental preservation, and climate change mitigation necessitate innovative solutions. Membrane technology, combined with the power of machine learning, emerges as a cornerstone for a cleaner and more sustainable future. In the realm of water treatment, membrane filtration processes such as reverse osmosis and nanofiltration provide sustainable solutions by efficiently removing contaminants from water sources. With a staggering 2 billion people lacking safe water access globally and a significant amount of untreated wastewater being released into the environment, the importance of membrane technology in providing clean water cannot be overstated. By minimizing the need for chemical treatments and offering effective filtration, membranes play a vital role in addressing water scarcity and contamination issues.

Furthermore, membrane technology contributes to the reduction of greenhouse gas emissions through selective gas separation. Carbon dioxide emissions have reached record levels in recent years, and membrane-based carbon capture and purification of industrial gases offer energy-efficient alternatives. By selectively separating different gases based on their molecular properties, membrane gas separation provides a cost-effective and environmentally sustainable solution for industries such as natural gas processing and hydrogen production. In the realm of energy production, membrane technology enhances efficiency and sustainability. Membrane-based fuel cells enable the efficient conversion of chemical energy into electricity, while membrane systems such as membrane reactors find applications in hydrogen production and carbon dioxide capture. By facilitating the transport of ions and preventing reactant mixing, membranes contribute to the advancement of clean and renewable energy sources. The integration of machine learning in membrane design and discovery revolutionizes the field by enabling accurate prediction of membrane properties and optimization of system performance. This integration leads to the development of specialized membranes tailored for specific applications, further enhancing the overall efficiency and effectiveness of membrane technology.

In summary, membrane technology, driven by machine learning, offers sustainable solutions for water treatment, gas separation, and energy production. With the potential to address water scarcity, reduce greenhouse gas emissions, and enhance energy production efficiency, membranes and machine learning represent a promising combination for a cleaner and more sustainable future. Continued research and development in this field will further unlock the full potential of membrane technology and contribute to the

Table 9 Versatile applications of nanofiltration membranes across diverse industries. In the chemical sector, nanofiltration membranes play a crucial role in recovering and purifying chemicals, extracting carbon dioxide, and eliminating impurities from process streams. In textiles, these membranes are employed to purge colorants and impurities, ensuring compliance with environmental regulations. The fine chemistry and pharmaceuticals industry benefits from nanofiltration membranes in isolating pharmaceutical compounds and purifying valuable intermediates. Additionally, nanofiltration membranes contribute to processes in the paper and pulp, agriculture, clothing and leather, natural essential oils, landfills, and optical/electronic and metal plating industries, showcasing their broad impact on various sectors

Industry	Applications of nanofiltration
Chemical	i. Recovering chemicals from bleaching solution ii. Removing sulfates before chlorine and sodium hydroxide production iii. Extracting carbon dioxide from process gases iv Preparing bromide v. Recovering caustic solutions used in cellulose and viscose rayon production vi. Precipitating calcium sulfate ($CaSO_4$) vii. Purifying chemical intermediates and final products viii. Recovering and concentrating valuable compounds ix. Eliminating impurities and contaminants from process streams x. Separating and recovering catalysts or solvents xi. Concentrating and purifying organic solvents
Textile	i. Purging colorants and impurities from dyeing and printing processes ii. Ensuring compliance with environmental regulations through the treatment of textile effluents iii. Separating and concentrating valuable compounds from textile waste streams iv. Purging organic contaminants from process water
Fine chemistry and pharmaceuticals	i. Separating antibiotics from pharmaceutical waste ii. Purifying and isolating pharmaceutical compounds iii. Eliminating impurities and byproducts from synthesis reactions iv. Concentrating on active pharmaceutical ingredients v. Recovering and purifying valuable intermediates vi. Removing organic impurities and colorants from process streams
Paper and pulp	i. Recovering and reusing chromium (III) and chromium (II) ii. Reclaiming water from wastewater or waste treatment effluent iii. Removing sulfates before chlorine and sodium hydroxide production iv. Recovering water and valuable chemicals from wastewater v. Extracting lignin and colorants from process streams vi. Reducing chemical usage in pulp bleaching vii. Treating effluents to comply with environmental regulations
Agriculture	i. Purging pesticides and heavy metals from groundwater ii. Eliminating algal toxins iii. Removing selenium and heavy metals from drainage water iv. Purifying leachate from landfills
Clothing and leather	i. Removing salts and impurities from leather processing streams ii. Treating effluents to minimize environmental impact iii. Recycling and reusing processed water iv. Eliminating organic contaminants and colorants v. Recovering water and salts from wastewater vi. Concentrating valuable components from process streams
Natural essential oils and similar products	i. Separating substances through gentle processes ii. Enhancing the concentration of natural compounds iii. Fractionating crude extracts
Landfills	i. Removing phosphate, fluoride (F^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) ii. Purification of landfill leachate

Table 9 (continued)

Industry	Applications of nanofiltration
Optical and electronic & Metal plating and product	i. Eliminating aluminum (Al^{3+}) from wastewater in the canning industry ii. Cleaning rinsing solutions used in machines iii. Removing nickel (Ni^{2+}) and copper (Cu^{2+}) ions from ore extraction liquids iv. Recovering and recycling metal salts and plating solutions v. Treating rinse water to minimize metal contamination vi. Concentrating and purifying metal ions for reuse vii. Removing organic contaminants and colorants from process streams viii. Separating and recovering valuable metals from complex mixtures ix. Purging metal sulfates from wastewater x. Separating heavy metals from acidic solutions

global pursuit of sustainable development and environmental preservation.

Disclaimer

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Declarations

Conflict of interest The authors declare no conflict of interest.

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