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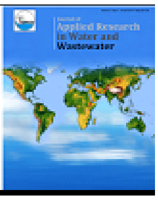
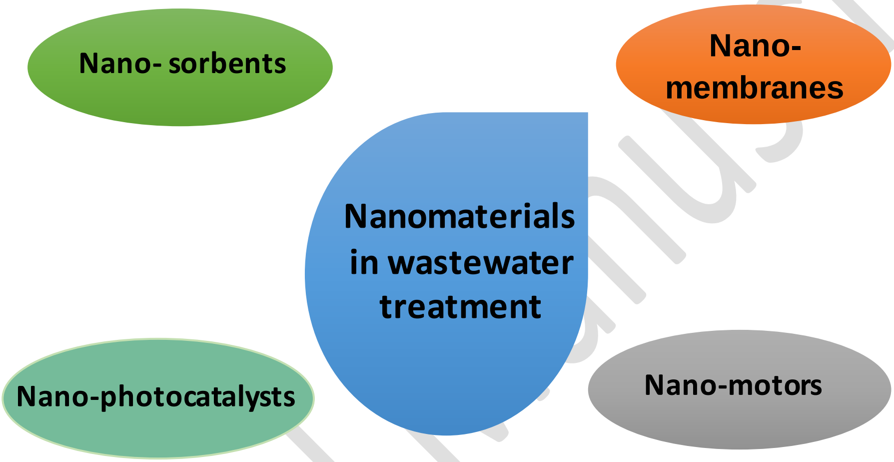


# Advancements and applications of nanomembranes for sustainable wastewater treatment: A technical perspective

**Nikta Shahcheraghi[1], Sahand Shafeei*[,2], Zahra Mostafaei[3], Soroush Namjoufar[4]**

[1]*Institute for Nanoscale Technology, Faculty of Engineering and Information Technology, University of Technology Sydney, Broadway, Australia.*
[2]*Department of Chemical and Biomolecular Engineering, The Grainger College of Engineering, University of Illinois Urbana-Champaign, Urbana, USA.*
[3]*Department of Chemical and Biological Engineering, Faculty of Engineering, University of Ottawa, Ottawa, Canada.*
[4]*Department of Environmental Engineering, College of Environment, University of Tehran, Kish International Campus, Kish, Iran.*

## GRAPHICAL ABSTRACT



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## ABSTRACT

Providing safe and clean water for a rapidly growing population is a critical global challenge. Nanotechnology-based membranes, or nanomembranes, represent a promising pathway toward sustainable wastewater treatment. Their ultra-thin, high-porosity structure can offer superior contaminant removal, enhanced flux, and lower energy consumption compared to conventional membranes. This review addresses both the fundamental principles and the latest advancements of nanomembranes, with an emphasis on the practical hurdles that currently impede widespread industrial adoption. Issues such as fouling, short operational lifespans, and cost barriers are discussed. In addition, the text highlights emerging materials and fabrication strategies, including two-dimensional (2D) nanosheets such as graphene oxide and MXenes, as well as composite membranes integrated with metal-organic frameworks or covalent organic frameworks. Real-world applications are summarized, along with a discussion of how specialized membrane designs can reduce fouling in large-scale treatment plants. The review concludes by proposing future research directions that could make nanomembrane technologies both economically viable and environmentally safe, and by illustrating how these novel systems can be scaled up to help achieve global clean-water sustainability goals.

## 1. Introduction

Safe water is fundamental to life, yet population growth and unplanned urbanization continue to strain limited freshwater resources and degrade overall water quality (Faisal, 2020; Wei *et al.*, 2021; Abouzeid *et al.*, 2019). Although conventional wastewater treatment methods are well-established, they often demand high energy, extensive maintenance, and can generate secondary pollution (Savage *et al.*, 2005). Consequently, more efficient approaches are essential to achieve the sixth Sustainable Development Goal of universal access to clean water.

Researchers have increasingly turned to nanotechnology, which offers promising routes to improve pollutant removal while simultaneously reducing overall energy consumption (Ahmad *et al.*, 2023). Nanostructures offer unique benefits, including extensive surface area, suitable porosity, photocatalytic capabilities, and the

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*Corresponding author Email: shafeei2@illinois.edu

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removal of heavy metals and persistent organic pollutants, thereby attracting significant scientific interest (Yaqoob *et al*., 2020; Shapira *et al*., 2021; Syahirah Kamarudin *et al*., 2021; Sharma *et al*., 2023). In wastewater treatment, nanomaterials frequently appear in forms such as nano-photocatalysts, nanomotors, nano-membranes, and nano-sorbents (Thirnavukkarasu *et al*., 2020; Wongcharee *et al*., 2017), but their applications extend well beyond water purification. They are being explored in agriculture, drug delivery, immunotherapy, nanosensors, nanobiochips, biodiesel production, and even cancer diagnosis (Zhang *et al*., 2021; Chester *et al*., 2021; Liu *et al*., 2021; Yoo *et al*., 2021; Zahed *et al*., 2021; Shahcheraghi *et al*., 2022). Within the water sector, nanomembranes are particularly compelling because of their ultra-thin architecture, controllable porosity, and distinctive surface properties (Homaeigohar, 2020). They can be fabricated from organic polymers, inorganic compounds, or hybrid composites, enabling the design of systems with high rejection rates for salts, heavy metals, and recalcitrant organic pollutants. Investigations into doping these membranes with metal oxides, carbon nanotubes, or two-dimensional nanosheets have reported increases in both permeability and selectivity (Abouzeid *et al*., 2019). Similarly, nanostructured metal-oxide surfaces such as MnOx have shown strong oxidative capabilities in harsh wastewater matrices, including saline produced water (Khorram *et al*., 2025). In addition, recent work has demonstrated that waste-derived polymers can be transformed into high-performance nanostructured materials for membrane fabrication. Ameh *et al*. (2025) demonstrated that upcycling waste polymers not only improves separation performance in water and wastewater treatment but also offers a sustainable route to reduce environmental impact. Even so, widespread industry adoption remains slow due to concerns regarding membrane fouling, operational lifespans, and the fate of released nanoparticles, while costs related to manufacturing, quality control, and large-scale deployment add further complications.

Recent studies have pointed to certain pathways that could help realize cost-effective, full-scale use of nanomembranes for wastewater treatment. One newly published work highlights the feasibility of scaling production while keeping expenses manageable (Paziresh *et al*., 2024). Researchers are also exploring greener synthesis routes that generate minimal by-products and are investigating how best to tailor membranes for niche applications, such as selectively targeting radioactive ions or emerging contaminants. Although the path to complete commercial integration is still evolving, it appears increasingly likely that nanomembranes will play a central role in next-generation water treatment, with the potential to deliver cleaner and safer water supplies under varying economic and environmental conditions. The sections that follow review the fundamental properties and fabrication methods of nanomembranes, the challenges they confront in large-scale plants, and future directions for transforming them into cost-effective, sustainable solutions for global water needs.

## 2. Nanomembranes

Nanomembranes represent a captivating subset of nanomaterials that have become a focal point in nanotechnology. They are typically defined as ultra-thin membranes, sometimes only a few nanometers thick, which can be freestanding or supported on various substrates (Agboola *et al*., 2016). Fig. 1 illustrates some of the ways nanomaterials, including nanomembranes, are employed in wastewater treatment, while Fig. 2 depicts how nanomembranes may be classified based on material type, porosity, or fabrication method (Z. Jakšić and O. Jakšić, 2020; Matovic and Jakšić, 2009).

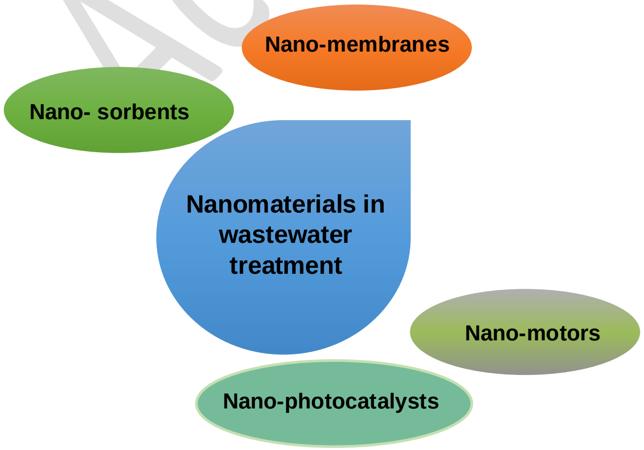

**Fig. 1.** Various nanomaterials employed in wastewater treatment.

Inorganic nanomembranes usually involve metals, semiconductors, or oxides such as titanium dioxide ($TiO_2$), zinc oxide (ZnO), and aluminum oxide ($Al_2O_3$). Organic nanomembranes are often polymer-based, formed from materials that include polyvinylidene fluoride (PVDF), polysulfone, or cellulose derivatives. Hybrid or composite nanomembranes incorporate both inorganic and organic elements in a single system, thereby combining high mechanical strength or photocatalytic activity with flexibility, fouling resistance, or selective permeability (Adiga *et al*., 2009). Researchers have taken a keen interest in these emerging membrane types because they allow exceptionally precise control over thickness, pore size, and surface functionalization, all of which affect the way contaminants are either repelled or adsorbed onto the membrane surface.

The core motivation behind using nanomembranes lies in their high selectivity, large surface-area-to-volume ratio, and tunable functionality. They can be designed to target specific pollutants in wastewater, such as heavy metal ions, recalcitrant organics, or microbial pathogens, and can often do so with reduced energy consumption compared to traditional filtration media. In the context of wastewater treatment, nanomembranes introduce novel functionalities that augment membrane performance. They can offer improved water flux, better separation efficiency, or even enhanced catalytic and antibacterial properties when doped with engineered nanomaterials. Although nanomembranes represent cutting-edge and environmentally friendly systems, their widespread adoption is still hindered by cost barriers. Many examples remain confined to laboratory-scale experiments, and the commercialization process is challenging because of issues like large-batch fabrication, long-term stability, and the unknown fate of nanoparticles that may detach from the membrane (Jedla *et al*., 2021).

Fig. 1 shows various types of nanomaterials that can be employed in water treatment: nano-photocatalysts, nano-sorbents, nano-membranes, and nano-motors (Thirnavukkarasu *et al*., 2020; Wongcharee *et al*., 2017). Beyond wastewater treatment, these and other nanomaterials find diverse applications in fields such as agriculture, drug delivery, immunotherapy, biosensing, and biodiesel production (Zhang *et al*., 2021; Chester *et al*., 2021; Liu *et al*., 2021; Yoo *et al*., 2021; Zahed *et al*., 2021; Shahcheraghi *et al*., 2022). Moreover, bio-nanomaterials have shown great promise in desalination processes. Singh *et al*. (2025) reported that incorporating green bio-nanomaterials into desalination systems can significantly enhance water flux and reduce membrane fouling, paving the way for more energy-efficient wastewater treatment. Nevertheless, the heart of recent developments has centered on exploiting the ultra-thin and highly specialized nature of nanomembranes to remove contaminants more effectively than conventional membranes. By carefully tuning the membrane's morphology, chemical functionality, and thickness, researchers have managed to boost ion rejection, reduce fouling, and even integrate catalytic reactions that degrade or transform unwanted substances.

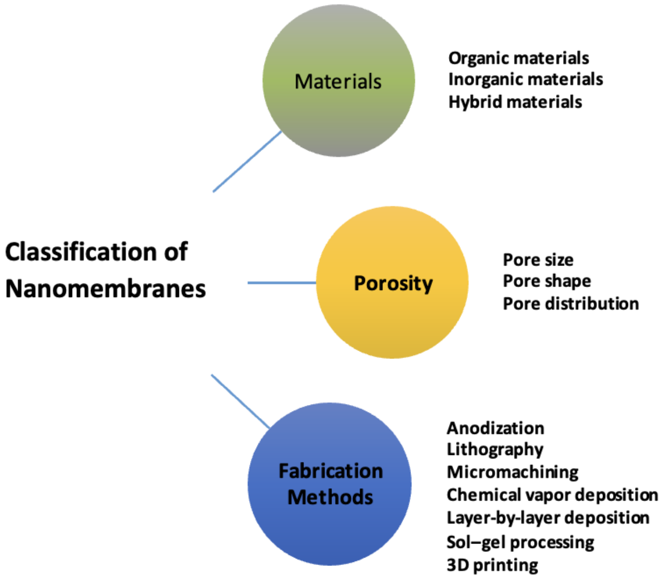

**Fig. 2.** Classification of nanomembranes

Fig. 2 provides an overview of classification schemes for nanomembranes based on structural features (porous vs. nonporous), material composition (inorganic, organic, or hybrid), and fabrication approaches (top-down exfoliation, bottom-up assembly, or solution-based techniques) (Z. Jakšić and O. Jakšić, 2020). Porous nanomembranes typically rely on sieving mechanisms, while nonporous types can rely on diffusion or complex chemical interactions to achieve selective separation. Fabrication methods vary from roll-to-roll processing of thin polymer films to chemical vapor deposition (CVD) of graphene-like sheets and from electrospinning polymeric mats to layer-by-layer assembly of metal oxide nanostructures. In each case, membrane characteristics such as pore size, membrane thickness, and surface chemistry must be carefully calibrated to match the intended application, be it desalination, removal of trace pollutants, or industrial waste recycling. From a practical standpoint, tailoring nanomembranes for real-world applications involves balancing performance benefits with economic viability and regulatory compliance. Although many experimental results highlight the promise of nanomembranes, further research and development are required to refine their antifouling properties, assure their safe disposal, and ensure that scaling-up production does not compromise membrane quality or integrity. Despite these challenges, the scientific community remains optimistic that next-generation nanomembranes will provide a significant leap forward in wastewater treatment technologies, enabling cost-effective, energy-efficient, and highly selective removal of the myriad contaminants that threaten water security. Table 1 summarizes selected nanomembrane types, their key materials, their main strengths, and representative real-world examples. This table distills many of the points discussed in subsequent sections and underscores how each category of nanomembrane can be aligned with different treatment goals.

## 3. Membrane distillation technology

Membrane distillation is a powerful separation technique that uses a vapor pressure gradient, created by temperature differences, across a hydrophobic porous membrane (Biniaz *et al.*, 2019). It can achieve high efficiency under relatively moderate conditions, making it compatible with low-grade industrial waste heat. The primary uses include wastewater treatment, seawater desalination, and the concentration of thermally sensitive compounds (Gola *et al.*, 2022). Depending on how condensation occurs, there are four membrane distillation configurations known as sweep gas membrane distillation, air gap membrane distillation, vacuum membrane distillation, and direct contact membrane distillation (Robbins *et al.*, 2020).

Despite its potential, membrane distillation consumes substantial energy in some setups, although the process temperature itself is not necessarily high. Nevertheless, it is considered a promising zero-liquid-discharge option because it can treat highly concentrated brines that are difficult to manage using conventional pressure-driven approaches (Jia and Wang, 2018). To address known challenges such as fouling and wetting, recent research has focused on creating novel membranes with advanced features like superhydrophobicity, self-cleaning surfaces, and enhanced anti-scaling properties. Hydrophobic polymers such as poly(vinylidene fluoride) (PVDF), polypropylene (PP), and polytetrafluoroethylene (PTFE) are frequently employed, with poly(vinylidene fluoride) being among the most popular due to its relatively high mechanical strength and chemical stability (Schwantes *et al.*, 2019). However, the hydrophobic character can also lead to fouling over time if the membrane surface becomes partially wetted (Rojjanapinun and Pagsuyoin, 2021). Various modification strategies attempt to create superhydrophobic surfaces capable of repelling water droplets and reducing contact time, thus preserving long-term performance. While significant progress has been made, the commercialization of large-scale membrane distillation will require consistent production of membranes that resist fouling in diverse wastewater streams (Rojjanapinun *et al.*, 2021).

**Table 1.** Representative nanomembranes for wastewater treatment.

| Nanomembrane Type | Key Material | Main Strengths | Real-World Examples | Supporting Citations |
|---|---|---|---|---|
| Inorganic Metal Oxides | Titanium dioxide, zinc oxide, zirconia, alumina | Strong mechanical and thermal stability, photocatalytic and antibacterial traits | Pilot-scale metal ion removal, industrial effluent treatment | Shayesteh *et al.* (2016); Alzahrani and Mohammad. (2014) |
| Carbon-based (including CNMs and CNTs) | Graphene oxide (GO), carbon nanotubes (CNTs) | High flux, large surface area, enhanced chemical stability | Oil–water separation, selective heavy metal removal in municipal plants | Liu *et al.* (2016); Verweij *et al.* (2007) |
| Mixed-matrix membranes (hybrid polymeric) | Polymers doped with nanoparticles or 2D nanosheets | Better fouling resistance and higher permeability | Municipal wastewater reuse with lower energy demand | Rostam *et al.* (2018); Zhao *et al.* (2015) |
| 2D nanomaterials (MXenes, TMDCs) | Transition metal dichalcogenides ($MoS_2$, $WS_2$), MXenes | Tailored nanochannels, good selectivity, emerging in advanced desalination | Lab-scale brackish water desalination studies | Rehman *et al.* (2020); Davoy *et al.* (2018) |
| MOF and COF Composites | Zr- or Fe-based MOFs and COFs with polymer matrices | Highly porous and customizable, potential for antibacterial or catalytic functions | Research-stage membranes for high-value reuse and specialized industrial separations | Anjum *et al.* (2019); Yang *et al.* (2020) |

## 4. Common types of nanomembranes

Nanomembranes have been extensively studied for their potential to provide selective separations in environmental applications. They can be categorized by material properties, fabrication routes, or porosity (Matovic and Jakšić, 2009). The sections below discuss several notable categories of nanomembranes, including transition metal dichalcogenides, MXenes, carbon nanomembranes, polyethersulfone membranes, and specialized thin-film composites. Each category is associated with different advantages, limitations, and industrial applications.

### 4.1. Transition metal dichalcogenides membranes

Transition metal dichalcogenides (TMDCs) have drawn interest because of their unique two-dimensional structure and tunable properties. These materials frequently appear as mono- or multilayer nanosheets of $MoS_2$, $WS_2$, or related compounds. Fabrication routes such as mechanical cleavage and chemical vapor deposition (CVD) have been used, although they can be inefficient for large-scale production (Jin *et al.*, 2019). Once prepared, both pristine nanosheets and layered membranes can be integrated into filtration systems to remove dyes, heavy metals, or salts from wastewater (Rehman *et al.*, 2020). One ongoing challenge is to ensure that these membranes exhibit sufficient mechanical stability for industrial use.

### 4.2. MXene membranes

MXenes, a rapidly emerging family of two-dimensional transition metal carbides or nitrides, have attracted attention for high water flux and strong chemical resistance (Hong *et al.*, 2019). Fabrication of MXene-based membranes generally follows similar approaches used for graphene oxide, including vacuum filtration or layer-by-layer assembly (Wang *et al.*, 2021). These membranes often exhibit hydrophilic surfaces and adjustable interlayer spacing, important for rejecting targeted ions. Despite promising separation performance and hydrophilicity, issues such as long-term stability and potential oxidation remain significant (Rehman *et al.*, 2020; Singha and Kumar, 2020).

### 4.3. Carbon nanomembranes

Carbon nanomembranes (CNMs) are ultrathin sheets typically produced from the cross-linking of aromatic self-assembled monolayers under irradiation (Turchanin and Gölzhäuser, 2016). While small-scale demonstrations have shown good mechanical properties and high selectivity, adapting them for large-scale wastewater treatment is still in its infancy (Werber *et al.*, 2016; Park *et al.*, 2017). Researchers have also used carbon nanotubes or graphene to enhance polymeric membranes. Beryani *et al.* (2017) used stabilized nano zero-valent iron in Fenton's processes to remove benzene and MTBE, thereby illustrating how carbon-based additives and iron species can be combined for advanced remediation. Although many of these studies are proof-of-concept, carbon-based nanomaterials continue to be attractive due to their potentially superior mass transport and robust chemical tolerance.

### 4.4. Polyethersulfone membranes

Polyethersulfone (PES) membranes are well-known in conventional filtration applications. Their mechanical strength, thermal stability, and chemical resistance can be further improved by incorporating nanomaterials (Chu *et al*., 2020). Examples of additives include graphene oxide for enhanced antifouling, halloysite nanotubes (HNTs) for higher porosity, or HNTs modified with polymeric layers to reduce fouling (Alkindy *et al*., 2019). An essential aspect of these approaches is to ensure a uniform distribution of nanoparticles in the polymer matrix and to maintain stable bonding that does not degrade under high-pressure or harsh chemical conditions. Polyethersulfone membranes continue to be widely studied for both their familiarity to industry and their capacity for functional modification (Sadeghipour *et al*., 2022; Moradi *et al*., 2023).

### 4.5. Thin-film nano-templated composite membranes

Thin-film nano-templated (TFNt) membranes are often produced by interfacial polymerization of monomers such as piperazine with trimesoyl chloride, sometimes in the presence of nanoparticles that serve as templates (Yang *et al*., 2017; Figovsky, 2020). This process can introduce beneficial properties such as antimicrobial activity or improved ion selectivity. TFNt membranes attempt to balance high water permeability with increased salt rejection. These membranes may also feature metal nanoparticles embedded in the active layer, helping to mitigate biofouling through localized antibacterial effects (Nikbakht Fini *et al*., 2020).

### 4.6. Thin-film composite membranes

Thin-film composite (TFC) membranes normally include an ultra-thin active layer on top of a porous supporting layer, with a substrate that provides structural stability (Zhang *et al*., 2021; Peng *et al*., 2022). Reverse osmosis membranes for desalination are often of this type, although TFC structures can also be designed for nanofiltration or forward osmosis. By adjusting the polymer chemistry in the active layer, it becomes possible to control the membrane's rejection capacity and flux (Idarraga-Mora *et al*., 2018). Relatively high operating pressures are common in TFC systems, so membrane durability is a key factor.

### 4.7. Thin-film nanocomposite membranes

Thin-film nanocomposite (TFN) membranes are a further refinement in which nanomaterials (for example, functionalized carbon nanotubes or metal-organic frameworks) are integrated into the active layer or the porous support. The incorporation of these nanoparticles can raise water flux, enhance salt rejection, or impart antibacterial properties (Valamohammadi *et al*., 2020). Some TFN membranes have been shown to break the conventional trade-off between permeability and selectivity by leveraging unique nanoscale transport pathways. However, ensuring a stable dispersion of nanoparticles remains essential to avoid inhomogeneities, clustering, or leaching of the additive.

## 5. Nanomembranes for wastewater treatment

Nanomembranes have emerged as a critical technology in wastewater treatment due to their remarkable ability to selectively remove contaminants while operating at low energy consumption. In this section, the discussion is organized into various sub-categories that reflect the diverse materials and fabrication strategies employed in developing these membranes. Each sub-section examines a specific type of nanomembrane—ranging from multilayered titania–γ-alumina structures to advanced metal–organic framework composites—and evaluates their unique characteristics, benefits, and challenges in practical applications. The following sub-sections detail the performance, fabrication methods, and industrial relevance of each nanomembrane category, providing a comprehensive overview of their role in modern water purification processes. Figure 3 shows schematic representations of several key nanomembrane types discussed in this section, highlighting their respective mechanisms for contaminant removal and water filtration.

### 5.1. Titania–γ-alumina multilayer nanomembranes

Titania–γ-alumina multilayer nanomembranes have been prepared by a sol-gel method in which γ-alumina and titania nanocrystallites were successively applied on alumina supports as a sub-layer and top-layer, respectively (Shayesteh *et al*., 2016). The resulting nanomembranes had a mesoporous structure, with an average pore size of about 5.8 nm, and showed high water permeability along with an ability to reject ions and microorganisms in model wastewater. The measured permeability decreased from 1 to 10 bar due to the increased flux, remaining nearly constant beyond 10 bar. These multilayered nanomembranes, which could reject ions up to about 25 percent, also proved quite effective against microorganisms.

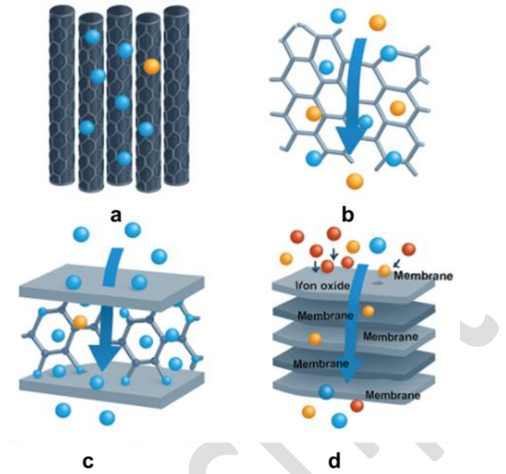

**Fig. 3.** Schematic illustrations of selected nanomembranes used in wastewater treatment. The illustrations demonstrate (a) carbon nanotube (CNT) channels showing water passing through vertically aligned channels while rejecting larger contaminants; (b) hexagonal boron nitride (h-BN) membranes depicting molecular sieving through nanoscale pores; (c) metal-organic framework (MOF) networks designed for heavy metal ion capture; and (d) iron oxide-based systems where magnetic particles assist in adsorption and recovery.

### 5.2. Carbon nano-tube membranes (CNT)

Carbon nanotubes, among the most intriguing nanomaterials discovered, have been widely investigated for high-performance polymer composite membranes (Liu *et al*., 2016). Their low density, high tensile strength, thermal conductivity, and large aspect ratio make them attractive for improving filtration. CNT membranes have shown considerable potential in diverse separation applications, including oil-water separation and dye removal, owing to their remarkable physicochemical and mechanical properties (Verweij *et al*., 2007). When embedded into polymeric membranes, CNTs can help achieve higher flux and enhanced solute rejection.

### 5.3. Hexagonal boron nitride nanomembranes

Hexagonal boron nitride nanosheets have been explored for water desalination because they can exhibit high chemical stability and distinctive adsorption capabilities (Davoy *et al*., 2018; Gao *et al*., 2017; Lei *et al*., 2013). Wu *et al*. (2016) demonstrated, through Monte Carlo simulations, that nanoporous h-BN nanosheets could separate water from salts by virtue of their pore size and shape. Gao *et al*. (2017) further reported that $N_4$-type h-BN nanopores achieved 100% salt rejection with water flux values several orders of magnitude higher than those of conventional RO membranes. Davoy *et al*. (2018) similarly showed that sub-nanoporous h-BN membranes demonstrated nearly 100% ion rejection and even outperformed nanoporous graphene in terms of water permeability. Loh (2018) found that doping h-BN with carbon atoms could yield water flux values ranging from 29.9 to 95.3 molecules/ns per pore, depending on the level of carbon content. Several researchers also confirmed that h-BN had a high capacity to adsorb pollutants such as arsenic ions (Srivastava *et al*., 2017). Although promising, larger-scale fabrication of h-BN nanomembranes that maintain consistent structure under industrial conditions remains a challenge (Shenoy *et al*., 2021; Loh, 2018).

### 5.4. Iron oxide nanomembranes

Iron oxide nanomaterials, often in forms such as magnetite ($Fe_3O_4$), maghemite ($\gamma$-$Fe_2O_3$), or hematite ($\alpha$-$Fe_2O_3$), are extensively studied for adsorption, oxidation, and degradation of pollutants (Lu *et al*., 2020). They can appear as stand-alone nanoparticles or as composites combined with carbon nanotubes or graphene. In water treatment applications, iron oxide nanomembranes can target dyes and heavy metals by leveraging magnetic properties for facile recovery of the adsorbent. Ongoing research seeks to improve their chemical stability and prevent aggregation.

### 5.5. Zeolite membranes

Zeolites, which are microporous aluminosilicate minerals, have been investigated for wastewater purification due to their well-defined pore structure (Aloulou *et al*., 2020). Zeolite nanosheets can be fabricated by top-down exfoliation or bottom-up synthesis techniques (Goh and Ismail, 2018). When produced as thin membranes, they offer the potential for precise molecular sieving. Fabrication challenges include controlling nanoscale crystal growth, ensuring strong attachment to supports, and achieving high-quality freestanding membranes. Zeolites are already employed in gas separation, catalysis, and adsorption. Their extension to large-scale aqueous filtration is still developing (Huang *et al*., 2021; Liu *et al*., 2016).

### 5.6. Carbon-based polymeric nanocomposite membranes

Carbon-based antibacterial agents, including single-walled or multi-walled carbon nanotubes, hollow carbon spheres, graphene oxide, and mesoporous carbon, can be used to modify polymeric membranes (Zahid *et al*., 2018). They can impart antibacterial, antifouling, and high-flux characteristics by disrupting bacterial cell membranes and offering large surface areas for adsorption. When embedded into polymeric matrices such as polysulfone or polyamide, carbon-based nanofillers may enhance water flux, salt rejection, and resistance to pollutants (Chan *et al*., 2016). Implementation at scale requires maintaining stable dispersion of carbon additives within the polymer matrix.

### 5.7. ZnO-based polymeric nanocomposite membranes

Zinc oxide offers anticorrosive, antimicrobial, and antifungal properties, making it a common additive in membranes formed from polysulfone, polyvinylidene fluoride, or polyethersulfone (Zhao *et al*., 2015). The inclusion of ZnO can improve hydrophilicity, porosity, and antifouling performance (Rostam *et al*., 2018). Some studies report that membranes embedded with ZnO exhibit self-cleaning under exposure to visible light, but this depends on doping levels and operating conditions.

### 5.8. Titanium dioxide-based polymeric nanocomposite membranes

Titanium dioxide is a popular choice for its strong photocatalytic properties, high stability, and low cost (Zahid *et al*., 2018; Hoseini *et al*., 2017). $TiO_2$-based nanocomposite membranes can degrade organic pollutants, reduce fouling, and function effectively in multiple filtration contexts (Alzahrani *et al*., 2014). One limitation is that $TiO_2$ typically requires UV light to drive its photocatalytic process, unless it is doped or chemically modified to respond to visible light. Efforts are ongoing to expand $TiO_2$ activity into a broader spectrum range while retaining its favorable antibacterial and antifouling characteristics.

### 5.9. Copper-based polymeric nanocomposite membranes

Copper nanoparticles, ions, and alloys are recognized for their strong antibacterial behavior, availability, and comparatively low cost (Ben-Sasson *et al*., 2014). They have been used to modify thin-film composite membranes (TFC) and can inhibit bacterial growth, thereby prolonging membrane life under fouling-inducing conditions. Modifications involving copper nanoparticles must ensure that copper does not leach excessively into the treated water, which would raise new environmental concerns (Zahid *et al*., 2018).

### 5.10. Silver-based nanocomposite membranes

Silver has broad-spectrum antibacterial properties and low cytotoxicity, making it a widely used agent for controlling biofouling (Zahid *et al*., 2018). When silver nanoparticles are anchored onto or embedded within membranes, they can greatly reduce microbial attachment. However, the cost of silver and the risk of nanoparticle release have led researchers to explore alternatives such as iron or copper, or to reduce silver usage by combining it with other biocidal materials.

### 5.11. Chitosan

Chitosan, a biodegradable and nontoxic biopolymer derived from chitin, can be functionalized with amino and hydroxyl groups that promote adsorption of pollutants such as dyes, metals, and pesticides (Kumar, 2000). Chitosan-based membranes may be produced by blending chitosan with other polymers or by cross-linking it with different agents for enhanced mechanical strength (Olivera *et al*., 2016). Although known for high adsorptive potential, chitosan membranes can suffer from relatively low chemical resistance and limited mechanical stability, necessitating the use of reinforcement materials.

### 5.12. Graphene-based nanomembranes

Graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO), have been extensively studied for membrane applications because of their exceptional mechanical, thermal, and chemical properties (Wei *et al*., 2018). Graphene nanosheets can provide high flux due to the presence of frictionless slip planes. They can also be engineered with nanopores to allow selective passage of water molecules while rejecting dissolved salts and organic contaminants (Cohen-Tanugi *et al*., 2015). One noted challenge is ensuring that these nanosheets are assembled or perforated uniformly, preventing any defects or cracks that would compromise separation performance (Mahmoud *et al*., 2015).

### 5.13. Nanocomposite membranes

Nanocomposite membranes generally refer to polymeric membranes enhanced with inorganic fillers such as metal nanoparticles, carbon nanotubes, metal-organic frameworks (MOFs), or other nanostructures (Alarifia *et al*., 2020; Wen *et al*., 2019). By altering membrane hydrophilicity, mechanical strength, or surface charge, these fillers can significantly improve antifouling characteristics and separation capability. Existing products, including commercial membranes that employ silver or titanium dioxide as embedded nanoparticles, testify to the growing market interest in nanocomposite solutions (Adugna, 2021). The main hurdles involve cost, stability, and reproducibility.

### 5.14. Fe-modified MMT

Fe-modified montmorillonite (Fe-modified MMT) has been dispersed in polycaprolactone–dichloromethane solutions to create adsorptive membranes with a strong affinity for removing arsenic from water (Lodo *et al*., 2019; Thirunavukkarasu *et al*., 2020). Montmorillonite, a clay mineral, can be modified with iron to enhance cation exchange capacity, and the resulting membranes can effectively capture heavy metals. Future optimization may involve testing in variable pH, temperature, or industrial effluent scenarios to assess performance reliability.

### 5.15. Sodium titanate nanobelt membrane

Titanate-based materials have attracted attention in the removal of radionuclides, owing to their ion-exchange properties and structural resilience (Li *et al*., 2012). Sodium titanate nanobelts can be assembled layer-by-layer with polyethylenimine to form flexible, self-supporting membranes. They have demonstrated rapid kinetics for removing $137Cs^{+}$ and $90Sr^{2+}$ from simulated nuclear wastewater (Wen *et al*., 2016). This process leverages negative charges on the titanate layer, exchanging them for target cations. Beyond nuclear wastewater applications, sodium titanate membranes can also exhibit photocatalytic properties that benefit general environmental remediation efforts (Cao *et al*., 2020).

### 5.16. Polyamide NF

Nanofiltration (NF) membranes composed of polyamides are known for their ability to remove small active organic molecules and multivalent ions (Cheng *et al*., 2017). Polyamide NF membranes are commonly made by interfacial polymerization of aromatic amines with acid chlorides, forming a thin film on a porous substrate (Xu *et al*., 2020). Researchers often dope this thin film with silica nanoparticles, silver, or other fillers to boost mechanical strength and achieve specialized separations. One challenge is to preserve the delicate balance between salt rejection and water flux without compromising membrane integrity in high-pressure environments.

### 5.17. Zirconium oxide

Zirconium oxide ($ZrO_2$) is a transition metal oxide with properties similar to titanium dioxide. It is used in membrane fabrication or modification to improve chemical and thermal resistance (Goh *et al*., 2016). $ZrO_2$ can be dispersed onto Nafion or sulfonated polyether ketone membranes to reduce methanol crossover in fuel cell applications or to enhance mechanical stability in water filtration (Pan *et al*., 2010). By adjusting concentrations and binding modes, one can tune membrane permeability and selectivity for specific contaminants, but large-scale manufacturing has not yet been widely demonstrated.

### 5.18. Nano-filtration membrane bioreactors

Nanofiltration membrane bioreactors combine biological treatment with membrane-based separation, providing an integrated method to remove both organic pollutants and suspended solids (Sari Erkan *et al*., 2018). The long solids retention time and high biomass concentration in a membrane bioreactor (MBR) enhance the removal of various pollutants, while the NF stage further refines water quality by rejecting smaller organics and multivalent ions (Pan *et al*., 2010). Despite these advantages, the accumulation of engineered nanoparticles can impact microbial diversity, and membrane fouling remains a concern for long-term operation (Meng *et al*., 2009).

### 5.19. Electrospun nanofiber membranes

Electrospun nanofiber membranes have emerged as a versatile class of filtration media due to their ability to form ultrafine fibers with diameters ranging from a few nanometers to several micrometers (Xue *et al*., 2019). In the electrospinning process, a polymer solution is extruded from a syringe under a high-voltage electric field, resulting in the formation of a Taylor cone that ultimately gives rise to a stable, continuous jet. As the solvent evaporates during flight, individual fibers are deposited onto a collector, assembling into a nonwoven mat. These mats are characterized by exceptionally high porosity, a large surface-to-volume ratio, and the capacity for tunable pore structures, making them highly effective in optimizing water flux and enhancing contaminant rejection (Faccini *et al*., 2015). Commonly used polymers such as polyacrylonitrile, poly(vinylidene fluoride), and polysulfone provide the structural backbone, while the incorporation of functional nanoparticles further augments the performance by introducing additional properties such as enhanced hydrophilicity, photocatalytic activity, or antimicrobial effects.

Extensive research has been dedicated to refining the electrospinning process to achieve optimal fiber morphology and consistent membrane performance. Researchers have meticulously adjusted parameters including solution concentration, applied voltage, needle-to-collector distance, and ambient conditions like temperature and humidity. These parameters influence fiber diameter, bead formation, and overall mat uniformity, which in turn affect the membrane's pore size distribution and mechanical integrity. In addition, advancements in collector design—such as rotating drum collectors or patterned substrates—allow for the alignment of fibers, thereby enabling the formation of membranes with anisotropic properties that can enhance directional water transport and improve mechanical strength under operational stress.

Beyond the initial fabrication, post-processing techniques play a critical role in determining the final properties of electrospun membranes. Thermal annealing, chemical cross-linking, and plasma treatment are among the methods employed to enhance fiber interconnectivity and stabilize the structure against mechanical deformation. Such treatments can also modify the surface chemistry, thereby improving antifouling characteristics and ensuring a more durable interaction with water molecules. For instance, surface functionalization with hydrophilic groups or the deposition of ultrathin coating layers can reduce the propensity for fouling by repelling oil or organic contaminants, thus maintaining high permeability over extended operational periods.

Despite these promising developments, several challenges persist. The inherently high surface area of electrospun membranes, while beneficial for filtration, can also predispose the material to accelerated fouling as contaminants are more readily adsorbed onto the fiber surfaces. Furthermore, the mechanical stability of these delicate fibrous mats under crossflow conditions remains a concern, as high shear forces may lead to the detachment of fibers or the leaching of functional nanoparticles. Researchers are actively exploring composite structures that integrate reinforcing elements—such as embedding nanofibers within supportive polymer matrices or laminating the nanofiber mat onto more robust substrates—to overcome these limitations without compromising porosity.

Additionally, the scalability of electrospinning poses another significant hurdle. While laboratory-scale production has demonstrated excellent filtration performance, transitioning to industrial-scale manufacturing requires the development of high-throughput processes that ensure consistency and uniformity across large membrane areas. Recent advances in needleless electrospinning and roll-to-roll production methods show promise in addressing these scalability issues, though further optimization and rigorous quality control are essential for successful commercialization.

Overall, electrospun nanofiber membranes offer substantial potential for advanced wastewater treatment. Their customizable structure, high porosity, and adaptable surface properties make them a prime candidate for next-generation filtration systems. Ongoing research efforts aim to balance high performance with durability and scalability, ensuring that these membranes can move from innovative laboratory prototypes to reliable, cost-effective solutions in industrial applications.

### 5.20. Metal organic frameworks (MOFs)

Metal organic frameworks (MOFs) are crystalline materials formed by the coordination of metal ions or clusters with organic ligands, yielding structures with exceptionally high porosity and a tunable framework. Their unique architecture allows for a high degree of customization, enabling researchers to tailor pore size, shape, and surface chemistry to target specific contaminants in wastewater (Anjum *et al*., 2016; Yekta *et al*., 2023). MOFs can be integrated into polymeric membranes either as dispersed fillers in a nanocomposite or as continuous layered structures prepared using techniques akin to those used for graphene oxide assembly (Yang *et al*., 2020).

A significant advantage of MOF-based membranes lies in their dual functionality. In some cases, MOFs have demonstrated antibacterial activity through the gradual release of metal ions, which helps reduce biofouling. In other cases, their inherent porosity and selective adsorption capabilities enable efficient removal of heavy metals, dyes, and organic pollutants. Researchers have also explored combining MOFs with covalent organic frameworks (COFs) to merge the benefits of both inorganic and organic chemistry, further enhancing selectivity and stability.

Despite these promising attributes, MOF-based membranes remain predominantly at the pilot or laboratory scale. Key challenges include ensuring long-term chemical and mechanical stability under continuous operation and developing cost-effective methods for large-scale synthesis. Furthermore, the trade-off between permeability and selectivity must be finely balanced to meet practical filtration requirements. Ongoing research aims to address these issues through novel synthesis approaches, improved integration techniques, and rigorous lifecycle assessments. With these advances, MOF-based membranes hold significant potential to serve as next-generation filtration materials for advanced wastewater treatment, provided that scalability and economic viability are ultimately achieved (Z. Jakšić and O. Jakšić, 2020).

### 5.21 Enzyme-integrated nanomembranes

Recent research has begun to explore the integration of biocatalysts with nanomembrane systems to achieve in situ degradation of recalcitrant organic pollutants. In this context, the work by Lee *et al*. (2005) provides valuable insights into the catalytic mechanism of Rieske dioxygenases such as PrnD. Their supplemental data, which includes EPR spectral analyses, sequence alignments, and NMR characterization of reaction products, deepens our understanding of how these enzymes convert aminopyrrolnitrin into pyrrolnitrin. The detailed examination of PrnD's structural and functional properties suggests that immobilizing such enzymes onto nanomembrane supports could yield a hybrid system combining the high selectivity of catalytic degradation with the efficient separation capabilities of nanomembranes. Such bio-nanocatalytic membranes hold promise for enhanced removal of specific organic contaminants that are challenging to eliminate through conventional physical filtration alone. By harnessing the inherent catalytic activity of enzymes like PrnD, future membrane technologies could simultaneously filter and degrade pollutants, thereby reducing fouling and prolonging membrane life while achieving superior treatment efficiency.

## 6. Challenges

Despite the promising performance of nanomembranes at the laboratory scale, several significant challenges impede their widespread adoption in industrial wastewater treatment. A foremost concern is membrane fouling, which remains a persistent issue. Fouling occurs when contaminants, ranging from colloidal particles and organic macromolecules to biofilms and inorganic precipitates, adhere to the surface or become entrapped within the membrane matrix. This phenomenon not only diminishes water flux but also increases the energy demands for maintaining system performance and ultimately shortens the operational lifespan of the membrane. While periodic cleaning through backwashing or chemical agents can restore performance to some extent, repeated cleaning cycles may lead to structural damage, further reducing membrane longevity and increasing replacement costs (Rashidi *et al*., 2015). In addition to fouling, the inherently short operational lifetimes observed with many nanomembranes constitute a significant technical and economic challenge. Under real-world operating conditions, membranes may lose efficiency within days or weeks due to the aggressive nature of industrial effluents. This short life is compounded by the uncertainty regarding the fate of nanoparticles that might detach during operation. Such leaching raises environmental concerns, as these nanomaterials may accumulate in ecosystems or impact human health. The need for frequent replacement not only elevates capital and operational expenditures but also introduces periods during which treatment efficiency is compromised. Another considerable challenge is the scalability of nanomembrane fabrication. Laboratory-scale methods, although highly effective in controlling membrane architecture and performance, often do not translate easily into mass production. High-throughput processes must maintain consistent quality, reproducibility, and uniformity across large membrane areas. The current state of manufacturing is characterized by relatively high costs, partly due to the need for specialized equipment and the rigorous quality control required for nanoscale features. Furthermore, integrating nanomaterials into polymeric matrices or onto substrates without compromising their beneficial properties represents an ongoing engineering hurdle. Economic viability remains intertwined with technical challenges. The cost of raw materials, energy consumption for production and maintenance, and the complexity of integrating these membranes into existing treatment systems all contribute to uncertainties in commercial applications. Although some studies have demonstrated that nanomembranes can operate at lower energy costs compared to traditional methods, the high initial investment and ongoing maintenance expenditures can deter widespread adoption. Furthermore, the environmental footprint associated with the synthesis and disposal of nanomaterials adds another layer of complexity to their economic and regulatory acceptance. Regulatory and safety concerns also form a critical barrier. There is an urgent need for comprehensive risk assessments that consider the long-term effects of nanoparticle release and accumulation in aquatic and terrestrial ecosystems. This is particularly important given that many nanomaterials have not yet been fully characterized for toxicity at the concentrations likely to be encountered in large-scale applications. These uncertainties can hinder both public acceptance and regulatory approval. In summary, while nanomembranes hold significant promise for revolutionizing wastewater treatment, issues related to fouling, short operational life, scalability, cost, and environmental safety must be resolved before they can be widely implemented. Continued research and development efforts are essential to address these challenges, refine manufacturing processes, and establish standardized protocols that ensure both performance and safety in industrial applications.

## 7. Conclusions

The path toward widespread industrial application of nanomembranes necessitates a coordinated research effort addressing both fundamental scientific challenges and practical engineering obstacles. Future research should prioritize the development of robust antifouling strategies. For example, novel surface functionalization techniques, including the use of zwitterionic coatings or biomimetic materials, may significantly reduce the rate at which contaminants adhere to the membrane. Incorporating self-cleaning mechanisms through photocatalytic or electrochemical processes could further extend operational lifetimes, thereby reduce maintenance frequency and lowering overall costs.

In parallel, research must focus on extending the operational lifespan of nanomembranes through advanced composite designs. Innovations in multilayered membranes, where a protective outer layer can be periodically renewed without discarding the entire membrane, could prove especially promising. Efforts to improve the stability of the nanomaterial-polymer interface are critical to minimize the risk of nanoparticle leaching, which not only undermines performance but also poses environmental risks. Comprehensive lifecycle analyses that track the production, operational performance, and eventual disposal or recycling of nanomembranes will be essential for establishing their sustainability credentials.

Scalability remains one of the most significant hurdles in moving from laboratory prototypes to commercial systems. Future work should explore advanced fabrication techniques such as needleless electrospinning, roll-to-roll processing, or 3D printing to enable high-throughput production without compromising the finely tuned properties of nanomembranes. Process optimization and automation, coupled with stringent quality control measures, will be necessary to ensure that large-scale production can meet the consistent standards required for industrial wastewater treatment.

Economic considerations must also be addressed. Research into the cost structures of both production and operation should aim to identify key cost drivers and develop strategies to mitigate them. For example, employing greener synthesis routes that use abundant, low-cost, or waste-derived feedstocks can reduce material costs and lower environmental impact. Moreover, integrating nanomembranes with renewable energy sources, such as solar-powered membrane distillation systems, may further enhance the economic feasibility by reducing energy expenditures.

Regulatory and safety issues represent additional frontiers for future research. Detailed toxicological studies and environmental impact assessments are needed to fully understand the long-term implications of deploying nanomembranes. Establishing industry-wide standards and protocols for the safe handling, operation, and disposal of nanomaterials will not only bolster public confidence but also facilitate smoother regulatory approvals.

In conclusion, nanomembranes represent an innovative and potentially transformative solution for wastewater treatment. Their unique properties offer significant advantages in terms of selectivity, efficiency, and energy savings. However, to fully realize their potential, the challenges of fouling, limited durability, scalability, cost, and environmental safety must be rigorously addressed. Continued interdisciplinary collaboration among material scientists, engineers, industry stakeholders, and regulatory bodies will be crucial in overcoming these hurdles. As research advances, it is likely that nanomembrane technologies will evolve into cost-effective, sustainable, and robust systems that play a pivotal role in ensuring access to clean water worldwide.

## Author Contributions

Nikta Shahcheraghi: Conceptualization, writing - original draft, methodology, supervision.
Sahand Shafeei: Writing - review & editing, methodology.
Zahra Mostafaei: Data collection and analysis.
Soroush Namjoufar: Data collection and analysis.

## Data availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## Conflict of Interest

The authors declare no conflict of interest.

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