Research Article

Recent Progress In Mxene Based Membranes For Pressure Driven Water Desalination Applications: An Overview

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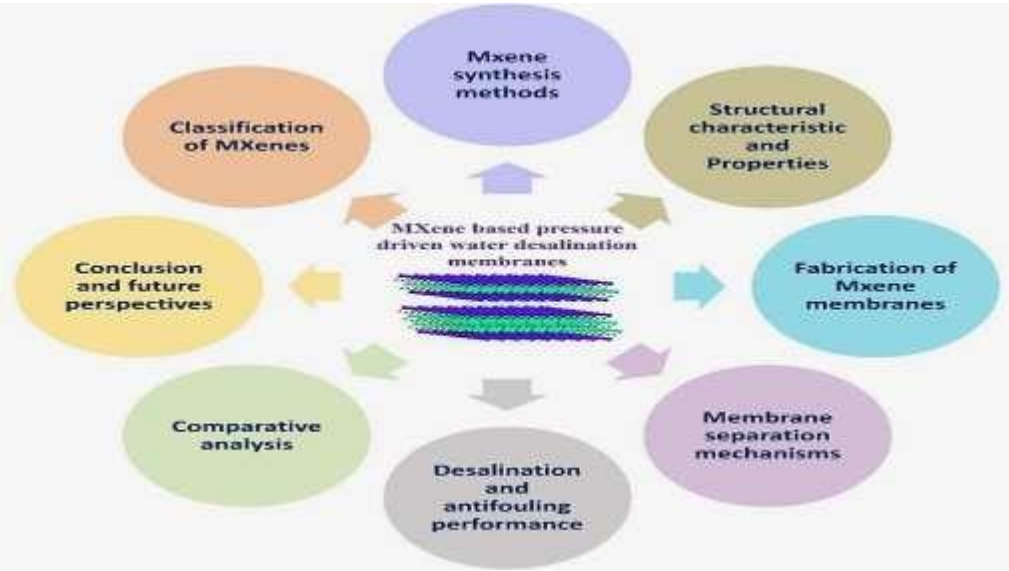
Abstract

The increasing global concern regarding water scarcity and contamination has necessitated the development of innovative and efficient water treatment technologies. Among these advancements, MXenes, two-dimensional (2D) transition metal carbides, nitrides, or carbonitrides have emerged as a promising class of materials due to their unique properties and functionalities. First synthesized in 2011, MXenes possess a unique combination of properties, including a two-dimensional layered structure, excellent electrical conductivity, intrinsic hydrophilicity, robust mechanical stability, and easily modifiable surface functional groups, making them highly attractive materials for the development of advanced membranes for water purification. The versatility of MXenes arises from their layered structure, allowing for easy exfoliation into thin nanosheets that can be manipulated to create membranes with tailored pore sizes and surface properties. These attributes enable the selective separation of contaminants from water, including heavy metals, organic pollutants, and salts. Furthermore, the incorporation of MXenes into traditional membrane matrices can enhance permeability while maintaining or improving selectivity a critical balance that is often challenging to achieve in membrane technology. Recent studies have focused on elucidating the mechanisms by which MXene-based membranes facilitate water treatment processes. Understanding these mechanisms is crucial for optimizing membrane design and performance. Simultaneously, advancements in fabrication techniques have led to the development of novel MXene-based composite membranes that improve the synergistic effects of MXenes with other materials to enhance functionality. As the field progresses, comprehensive evaluations of the performance of MXene membranes in various water treatment scenarios are essential for assessing their viability for real-world applications. In this review, we discuss in detail on the recent developments in MXene-based membranes for water treatment applications by exploring their unique properties, mechanisms of action, advancements in fabrication technologies, and performance metrics. Additionally, this review explores future directions and research opportunities that could further enhance the progress of MXene-based membranes toward practical implementation in addressing global water challenges.

Graphical Abstract



Keywords: MXenes, Membranes, Water treatment, Desalination, separation mechanism, Antifouling.

1. Introduction

In the context of ongoing climate change, rising global population, and expanding industrial activities, ensuring access to clean water has become critical for achieving a sustainable future. Beyond conventional water scarcity challenges, emerging contaminants such as microplastics, pharmaceutical residues, and radioactive substances pose significant risks that must be effectively addressed to ensure water safety [1, 2]. In response, considerable research efforts have been directed toward developing advanced water treatment technologies. Among these, membrane-based separation processes have attracted substantial interest due to their benefits, including low energy requirements, compact system design, and cost-effective operation [3, 4].

Two-dimensional (2D) nanomaterials such as graphene oxide (GO) [5, 6], metal–organic frameworks (MOFs) [7-9], covalent organic frameworks (COFs) [10], and MXenes [11] have recently emerged as promising candidates for water purification applications, owing to their atomic-scale thickness, large specific surface area, and tunable surface functionalities. These materials enable the fabrication of laminar membranes with precisely defined nanochannels, facilitating rapid transport of molecules or ions while maintaining high selectivity, which is a significant improvement over conventional polymer-based membranes [12]. Among them, MXenes offer several advantages, including hydrophilicity, antibacterial activity, thermal stability, electrical conductivity, and the presence of functional metal hydroxide sites, making them particularly attractive for advanced membrane development. These characteristics make it possible to engineer MXene-based membranes with multifunctional capabilities, including antibacterial, stimuli-responsive, and catalytically active features.

Ti_3C_2Tx (where Tx represents surface terminations such as –F and –OH) is the most extensively investigated MXene variant and is widely regarded as a versatile building block for the design of membranes capable of highly selective molecular or ionic separations [13-16]. Its unique chemical, thermal, and mechanical properties contribute to its effectiveness in separation technologies. Despite these advantages, several challenges still hinder the practical deployment of MXene membranes. These include the well-known permeability-selectivity trade-off, excessive swelling in aqueous environments, susceptibility to membrane fouling, and oxidation-related degradation [17]. The narrow interlayer spacing between adjacent nanosheets in MXene membranes often leads to imperfect stacking, contributing to reduced water permeability when aiming for high selectivity [18-20]. Moreover, water-induced swelling enlarges interlayer distances, compromises membrane structural integrity, and lowers separation performance [21, 22]. Fouling remains a persistent issue in membrane systems, as it diminishes operational efficiency and shortens service life while increasing energy demands [23, 24]. Additionally, MXene membranes are prone to oxidation when exposed to humid environments or elevated temperatures, primarily due to exposed titanium atoms acting as active oxidation sites on the surface [25-27]. Therefore, future research must focus on innovative design strategies that address these critical limitations particularly by mitigating the permeability-selectivity trade-off, enhancing mechanical and chemical stability, and improving resistance to fouling and oxidative degradation.

In this review, we present a comprehensive overview of MXenes including their classification and unique properties and various synthesis methods, we then discuss in detail on the recent developments in MXene-based membranes and their fabrication strategies for water desalination applications by exploring their unique properties, separation mechanisms of action, advancements in fabrication technologies, antifouling properties and comparison of performance metrics. Additionally, this review explores future directions and research opportunities that could further enhance the progress of MXene-based membranes toward practical implementation in addressing global water challenges.

2. Overview of MXenes and Their Unique Properties

This section provides a comprehensive overview of MXenes, a class of two-dimensional materials with remarkable properties, which have garnered significant attention in water treatment applications. We will explore their definition and classification, synthesis methodologies, distinctive structural characteristics, and the various functionalization techniques employed to enhance their performance and applicability in membrane technologies. Through this examination, we aim to elucidate the intrinsic attributes that render MXenes particularly advantageous for advancing water purification processes.

2.1 Definition and Classification of MXenes

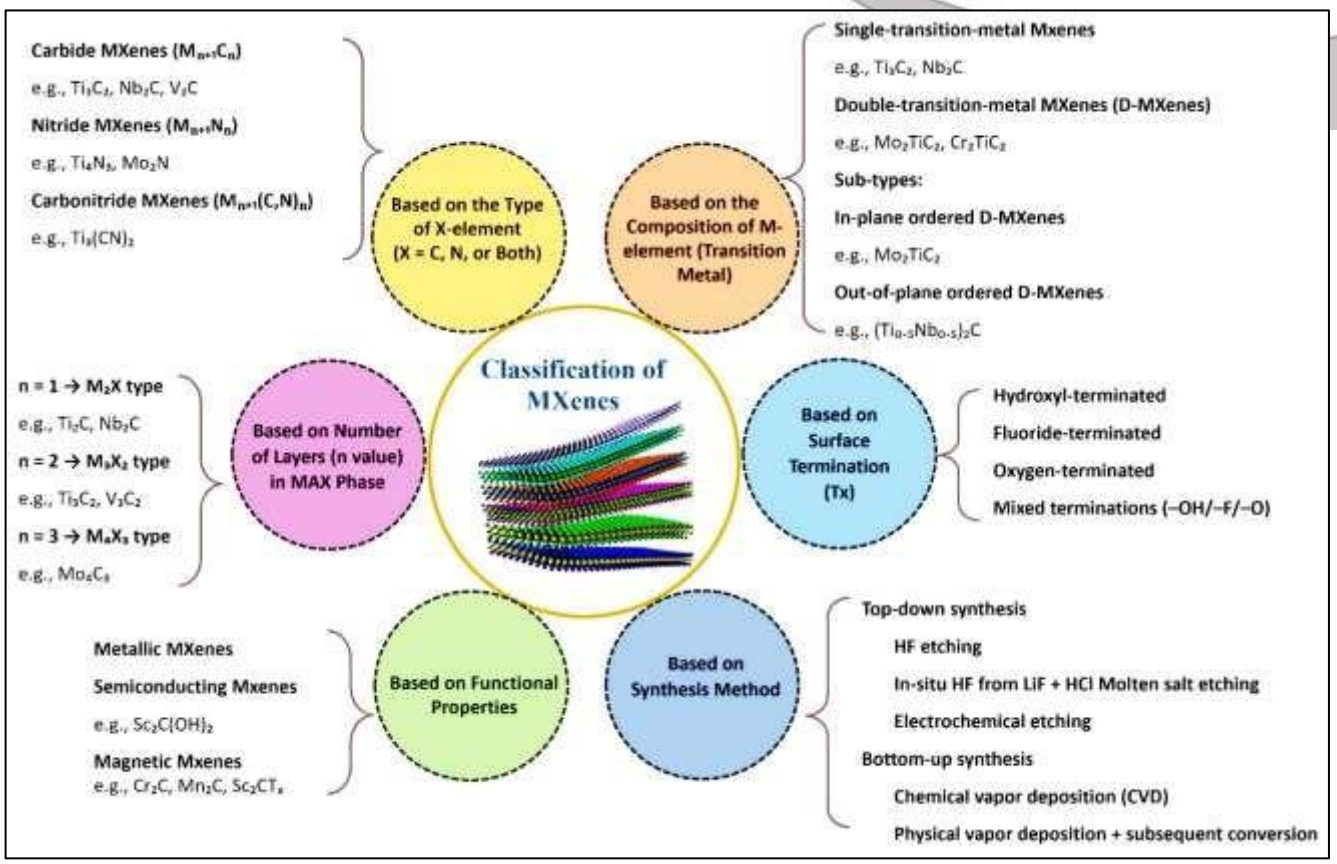


Fig. 1 Classification of Mxenes with examples.

MXenes are a novel class of two-dimensional materials comprising transition metal carbides, nitrides, or carbonitrides, first reported in 2011 by Yury Gogotsi and Michel Barsoum. They are derived from MAX phases (ternary carbides/nitrides with formula $M_{n+1}AX_n$) by selectively etching out the A-layer (typically group 13-16 elements). MXenes differ in their unique layered architecture and adaptable surface chemistry. This intrinsic versatility allows for strategic modifications aimed at optimizing their efficacy in water treatment applications. Classification of MXenes depends on their chemical composition and structural attributes, with significant categories encompassing those derived from early transition metals, such as Ti_3C_2, and variants incorporating functional groups that markedly influence their adsorption capabilities and interactions with a variety of aqueous contaminants. Understanding these foundational aspects is crucial for leveraging the potential of MXenes in advancing membrane technologies for enhanced water purification processes.

2.2 Synthesis Methods for Mxenes

The synthesis of MXenes has undergone significant refinement in recent years, particularly through advancements in selective etching techniques such as hydrofluoric acid and fluoride salt methods, which have markedly improved both yield and purity. These developments are crucial for the effective integration of MXenes into water treatment membranes, enhancing their functional efficacy. Additionally, novel synthesis approaches, including electrochemical and ultrasonic-assisted techniques, afford researchers enhanced control over the morphological characteristics and surface functionalization of MXenes, thereby optimizing their applicability in contaminant removal processes. This evolving landscape of synthesis methodologies highlights the potential for tailoring MXene properties to meet specific requirements in membrane-based water treatment applications.

Researchers have explored various approaches for synthesizing MXene nanosheets, which are generally categorized into two main methods: top-down and bottom-up techniques. Furthermore, MXene synthesis can also be distinguished based on the type of MAX phase precursor and the etching agent employed. Choosing an appropriate synthesis route is crucial for optimizing membrane characteristics to suit specific application needs. Fig. 2 illustrate the strategies for MXene synthesis.

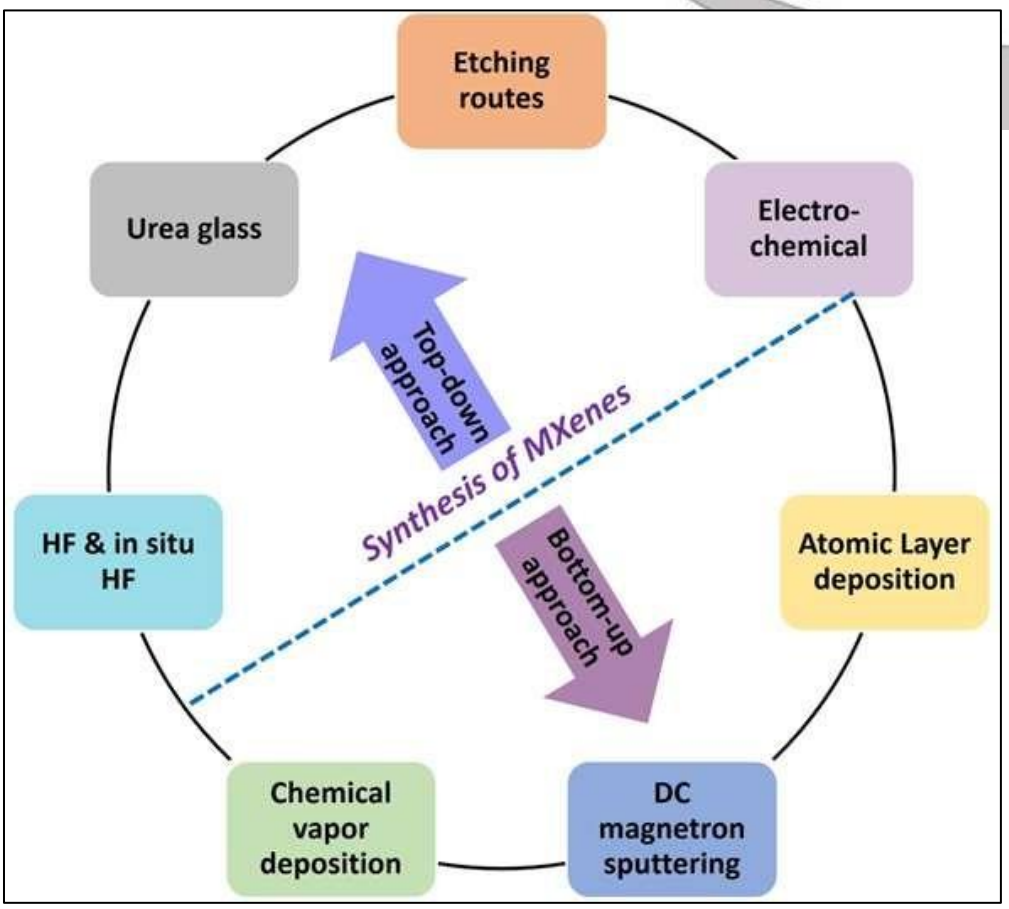


Fig. 2 Different methods for the synthesis of MXenes.

2.2.1. Top-down synthesis methods

The most widely adopted technique for synthesizing MXene nanosheets is a top-down method. This process typically begins with the selective etching of a MAX phase precursor, such as Ti_3AlC_2. In this structure, "M" stands for an early transition metal, "A" denotes a group IIIA or IVA element, and "X" represents either carbon or nitrogen, with n values ranging from 1 to 3. The etching process specifically targets the M–A bonds, which are generally weaker than the M–X bonds, allowing for the removal of the A-layer elements. To facilitate this, a high concentration of fluoride ions (F^-) is required, as they effectively react with the A-layer elements. This is commonly achieved by generating hydrofluoric acid (HF) in situ through the reaction of hydrochloric acid (HCl) with a fluoride-containing salt. This approach offers a safer alternative to direct HF use, mitigating its hazardous effects. Following etching, the second step involves the delamination of the resulting MXene material. This is done using intercalating agents combined with ultrasonication to increase the interlayer spacing. Typical intercalants include polar solvents such as dimethyl sulfoxide (DMSO), isopropyl alcohol (IPA), tetramethylammonium hydroxide (TMAOH), and tetrabutylammonium hydroxide (TBAOH). Ultrasonication helps to further reduce interlayer friction, promoting the formation of single-layer MXene nanosheets [28, 29].

Although the most common top-down method for MXene synthesis typically relies on etching with fluoride-containing agents, an alternative electrochemical etching technique was introduced by Sun et al. (2017) [30]. This method utilized an aqueous HCl electrolyte and excluded the use of fluoride ions, leading to MXenes terminated solely with –Cl, –O, and –OH groups. In a related development, Pang et al., presented a thermally-assisted electrochemical etching process for producing various MXenes, including Ti_2CT_x, Cr_2CT_x, and V_2CT_x. This approach enhanced the etching kinetics by applying moderate heating at around 50 °C [31].

2.2.2. Exfoliation based on MAX-phase

Various MAX phases have been employed as precursors in the synthesis of MXenes, each characterized by their unique structural and compositional attributes. These materials typically consist of alternating layers of transition metals and covalently bonded elements. Among them, Ti_3AlC_2 is one of the most extensively investigated due to its suitability for

producing MXenes like Ti_3C_2. In a notable study, Fan Liu explored the etching of Ti_3AlC_2 and Ti_2AlC using different fluoride-containing salts in hydrochloric acid (HCl), successfully synthesizing Ti_3C_2 and Ti_2C MXenes. These resulting two-dimensional materials hold promising potential for applications in the adsorption and storage of natural gases [32]. Fanfan Liu and colleagues successfully synthesized a highly pure form of two-dimensional V_2C MXene carbide by etching V_2AlC using a combination of sodium fluoride and hydrochloric acid at 90 °C over a period of 72 hours. Characterization techniques such as X-ray diffraction (XRD), energy-dispersive spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS) confirmed that the resulting V_2C MXene had a purity exceeding 90 weight percent, with only minimal residual phases like $Na_5Al_3F_{14}$ and unreacted V_2AlC. This method yielded a significantly higher purity product compared to traditional hydrofluoric acid (HF) etching performed at room temperature [33].

Following this, Meng Wu conducted a study to understand how different etching solutions influence the synthesis of two-dimensional vanadium carbide (V_2C MXene). The synthesis was carried out at 90 °C using three types of etching mixtures: lithium fluoride with hydrochloric acid (LiF + HCl), sodium fluoride with hydrochloric acid (NaF + HCl), and potassium fluoride with hydrochloric acid (KF + HCl). Among these, only the NaF + HCl combination successfully produced high-purity V_2C MXene. This outcome highlighted the importance of the presence of sodium (Na^+) and chloride (Cl^-) ions in the etching process. Thermogravimetric analysis coupled with differential thermal analysis revealed that the synthesized V_2C MXene remains thermally stable in an argon atmosphere up to 375 °C [34].

In a subsequent study, the same group explored how the synthesis environment affects both the structural quality and electrochemical properties of V_2C MXene. They carried out selective etching of V_2AlC at 90 °C under two conditions: an open environment (OE), using oil baths at atmospheric pressure, and a closed environment (CE), employing hydrothermal reactors under elevated pressure. Although both processes were maintained at the same temperature, the V_2C MXene obtained from the CE setup exhibited a higher degree of purity and better multilayer morphology than the samples from the OE setup [35]. In another study, using a hydrothermal-assisted method, Wang et al. successfully synthesized high-purity V_2CT_x MXene by etching V_2AlC with a mixture of fluoride and hydrochloric acid. This approach was demonstrated to be safer and less hazardous than conventional techniques [36].

Patrick and co-workers were the first to report the synthesis of Ti_4N_3-based MXene, marking the discovery of a two-dimensional transition metal nitride. Unlike conventional MXene synthesis methods that typically use aqueous acidic solutions to selectively etch the A-layer from MAX phase precursors, their approach employed a molten fluoride salt to remove aluminum from Ti_4AlN_3 powder. This reaction was carried out at 550 °C under an argon atmosphere. The resulting material was then subjected to a delamination process to produce few-layer and monolayer $Ti_4N_3T_x$ nanosheets, where T denotes surface terminations such as fluorine (F), oxygen (O), or hydroxyl (OH). Density functional theory (DFT) simulations suggested that both pristine and terminated Ti_4N_3 structures exhibit metallic conductivity. However, the inclusion of surface terminations was predicted to significantly suppress their magnetic properties [37].

The selection of a suitable MAX phase for synthesizing MXenes is guided by the specific properties desired in the final material and the intended application. Continued research is essential to refine the synthesis processes for various MAX phases and to fully harness the capabilities of MXenes. For example, Yitong et al. successfully synthesized high-purity Mo_2CT_x MXene from Mo_2Ga_2C using a hydrothermal etching approach. This method involved treatment at temperatures between 140 °C and 180 °C for 24 hours. Rather than employing the conventional hydrofluoric acid (HF) method, the researchers utilized alternative etching agents such as lithium fluoride (LiF), sodium fluoride (NaF), potassium fluoride (KF), and ammonium fluoride (NH_4F), each in combination with hydrochloric acid (HCl). Notably, the use of NH_4F with HCl enabled effective etching at the lower temperature of 140 °C, offering a safer and potentially more controlled synthesis route compared to traditional high-temperature or HF-based methods [38].

2.2.3. Exfoliation based on etchants

Various types of etchants are available for this purpose, each offering distinct properties and advantages. Among them, hydrofluoric acid (HF) etching is the most widely employed technique. Nonetheless, alternative approaches such as in-situ generation of HF using fluoride salts, molten salt-based etching, and alkali etching have also been developed. The subsequent sections provide a concise overview of these different etching methods [39, 40].

a) HF etching

One of the initial demonstrations of MXene synthesis involved the use of hydrofluoric acid (HF) to etch the MAX phase material, specifically producing $Ti_3C_2$from Ti_3AlC_2, as shown by Naguib et al. [41]. Later, Li et al., noted that performing this selective etching at room temperature posed difficulties, and elevated temperatures particularly around 60 °C proved more effective. Their study identified that the ideal conditions for MAX phase etching were maintaining the reaction at 60 °C for

24 hours in a 49% HF solution. While HF is highly efficient in removing the A-layer elements due to its strong acidity, it is also extremely toxic and corrosive, necessitating stringent safety measures during handling and disposal [42].

b) Fluoride salt/strong acid etching.

To address the challenges associated with using concentrated hydrofluoric acid (HF) directly, Ghidiu et al., introduced an alternative etching strategy that generates HF in situ by reacting hydrochloric acid (HCl) with a fluoride salt. This approach allows for the effective removal of the aluminum layer from MAX phases while minimizing the hazards linked to handling strong HF, as both HCl and salts like lithium fluoride (LiF) are comparatively safer. Additionally, the presence of Li^+ ions in the etching mixture aids in achieving well-delaminated MXene sheets with desirable properties [43]. Beyond LiF, other fluoride salts such as potassium fluoride (KF), sodium fluoride (NaF), and ammonium fluoride (NH_4F) have also been explored as alternatives in combination with HCl. Interestingly, unlike LiF, which tends to leave lithium residues on the MXene surface, KF and NaF result in negligible potassium or sodium residue [32]. The choice of fluoride salt can significantly influence the purity of the resulting MXene, depending on the specific MAX phase used. For example, Wu et al., demonstrated that among various fluoride salts tested with HCl, only the combination of NaF and HCl successfully produced high-purity V_2C MXene from the V_2AlC precursor [34].

c) Molten salt etching

In addition to traditional aqueous-based etching methods for MAX phases, alternative approaches involving molten salts and alkalis have also been explored at elevated temperatures. One of the initial studies in this area, reported by Urbankowski et al., demonstrated the synthesis of $Ti_4N_3$from Ti_4AlN_3using molten fluoride salts. Likewise, Li et al., employed molten $ZnCl_2$ to convert Ti_2ZnC and Ti_3ZnC_2 into Cl-terminated MXenes such as Ti_2CCl_2 and $Ti_3C_2Cl_2$. The molten fluoride technique typically results in F-terminated MXenes, whereas molten $ZnCl_2$ yields Cl-functionalized surfaces [34, 44, 45].

A more versatile strategy was later introduced allowing the synthesis of MXenes with a wide range of surface terminations, including O, S, Cl, Br, NH, Te, Se, and even pristine MXenes devoid of surface groups. This method begins by etching MAX phases using molten $CdBr_2$to obtain Br-terminated MXenes, which can then undergo further modification through substitution reactions to introduce various surface terminations or generate vacancies [45].

d) Alkali-Based Etching

Early work on alkali-mediated etching was carried out by Xie et al., who treated Ti_3AlC_2 MAX phases with a diluted NaOH solution at around 80 °C. However, due to the low concentration of NaOH, only the outer layers of the MAX phase were etched. Later, Zhang et al. developed a hydrothermal approach utilizing NaOH, significantly improving etching efficiency and achieving a yield as high as 92% [46]. In this method, hydroxide ions attack the Al layers within the MAX phase, leading to the formation of aluminum hydroxide or oxides. These intermediates dissolve in the alkaline medium to produce soluble $Al(OH)^-_4$ species. Etching efficiency can be greatly enhanced by increasing both the NaOH concentration (to 27.5 M) and reaction temperature (up to 270 °C).

Although alkali etching allows the synthesis of MXenes rich in –OH and –O surface terminations, it involves harsh conditions that can increase safety risks. For instance, Zhang et al., observed that immersing $Ti_3C_2T_x$ MXene in a 5 M KOH solution at 50 °C for 10 days led to the breakdown of the Ti–C framework. This degradation resulted in the formation of titanium oxide nanoparticles, which subsequently reacted with KOH to form $K_2Ti_8O_{17}$ nanowires [47].

In summary, the selection of an etchant for MXene synthesis must consider multiple factors, including the efficiency of the etching process, toxicity, material stability, and the nature of desired surface terminations. The ability to tailor MXene properties through careful etchant selection broadens their potential for diverse technological applications.

2.2.4. Bottom-up methods

The bottom-up approach presents an alternative method for synthesizing MXenes. Unlike the top-down method, which involves etching a precursor material, the bottom-up technique builds the desired structure by assembling individual atoms or molecules into layered configurations. Among the various techniques used in this approach, chemical vapor deposition (CVD) is the most commonly employed due to its ability to produce high-quality nanosheets on diverse substrates.

One of the earliest studies utilizing CVD for MXene synthesis demonstrated the deposition of Mo_2C nanosheets with excellent physical characteristics. In this process, methane served as the carbon source for a molybdenum/copper foil substrate heated to 1085 °C. Furthermore, by substituting molybdenum foil with tungsten or tantalum foils, researchers successfully synthesized ultrathin and high-quality WC and TaC crystals that remained stable under ambient conditions [48]

In a separate study, MoCu acted as a catalyst for the in-situ growth of two-dimensional Mo_2C layers on graphene using ambient pressure CVD. The resulting Mo_2C nanosheets were oriented vertically on the graphene surface. As the graphene layer formed, it passivated the catalyst surface, inhibiting Mo atoms in the MXene precursors from reacting directly with methane. This altered the growth mechanism from being precipitation-limited to diffusion-limited [49].

Additionally, Zhang et al., reported the fabrication of continuous, ultrathin, single-crystalline Mo_2C films with a face-centered cubic structure using a plasma-enhanced pulsed-laser deposition technique at a temperature of 700 °C [50]. Another noteworthy bottom-up strategy involves the reduction of two-dimensional hexagonal oxides in an ammonia atmosphere. This method enabled the synthesis of sub-nanometer thick 2D nitrides such as MoN. It also proved successful in producing other nitrides like W_2N and V_2N, demonstrating the method's adaptability [51].

Despite the benefit of producing pristine, ultrathin MXene crystals, bottom-up methods often face challenges such as low yield and process complexity. Nevertheless, with ongoing optimization such as temperature reduction, improved copper etching, and waste minimization this approach holds promise for cost-effective, scalable MXene nanosheet production.

3. Structural Characteristics and Material Properties

The structural characteristics and material properties of MXenes are pivotal in elucidating their efficacy as advanced membranes for water treatment applications. These two-dimensional materials exhibit a distinctive layered architecture that allows for tunable interlayer spacing, which is instrumental in facilitating selective ion transport and enhancing permeability. Additionally, the surface chemistry of MXenes, characterized by diverse functional groups such as -OH, -O, and -F, significantly influences their hydrophilicity and anti-fouling attributes, thereby optimizing membrane performance under operational conditions. Exploring these aspects provides insights into how structural and chemical modifications can be leveraged to improve the functionality of MXene-based membranes in addressing contemporary water purification challenges.

3.1. Favourable properties of MXenes for membrane-based water desalination

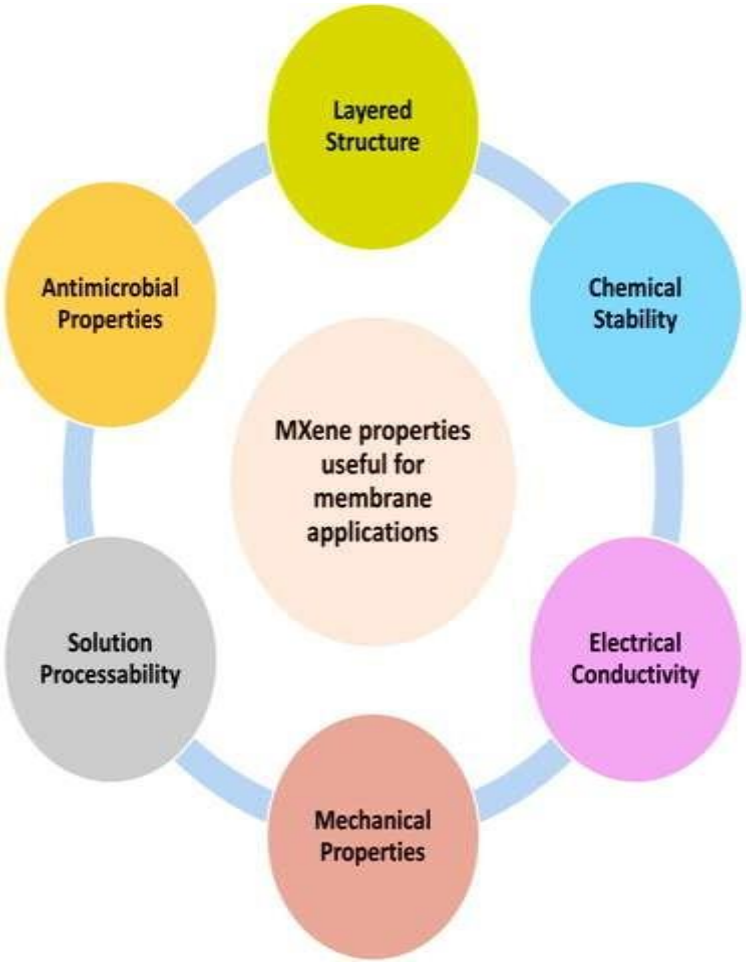


Fig. 3 Various properties of Mxenes useful for membrane applications.

To engineer high-performance membranes, it is essential to understand and harness the intrinsic material properties suitable for membrane fabrication. MXenes possess several structural and functional characteristics that make them excellent candidates for water desalination applications:

(a) Layered/Two-Dimensional (2D) Structure: MXenes feature a layered 2D architecture with a high aspect ratio, which enables the formation of nanochannels that facilitate solute diffusion. These nanochannels are generated through interstitial spaces between wrinkled or aligned nanosheets, defects within the crystalline lattice, and slits along nanosheet edges. Such channel structures diversify the transport rates of solutes, thereby influencing membrane selectivity. Additionally, the tunable interlayer spacing allows for the design of precise pathways to enable ion or molecular separation based on size exclusion. By modifying the etching and exfoliation processes, the lateral size of these nanoflakes can be adjusted within the range of 6 μm to less than 1 μm [19]. Moreover, like other 2D materials, MXenes are not entirely planar and often exhibit crumpled morphologies, enhancing their microstructural features beneficial for desalination.

(b) Mechanical Properties: Mechanical robustness is crucial for membranes subjected to hydraulic pressure during desalination. Single-layer $Ti_3C_2T_x$ MXene has demonstrated a notable Young's modulus of approximately 0.33 TPa, indicating superior elasticity compared to materials like graphene oxide and other solution-processable 2D systems [52]. When combined with polymers such as polyvinyl alcohol (PVA) or polydimethylsiloxane (PDMS), these MXene-based composites show further enhancement in mechanical stability.

(c) Solution Processability: Due to their hydrophilic nature, MXenes are highly dispersible in aqueous media a key requirement for membrane fabrication processes. This hydrophilicity stems from surface functional groups such as fluorine, oxygen, and hydroxyl (–OH), the latter also contributing to the material's negative surface charge. These functional groups facilitate electrostatic interactions and further chemical modification. The resulting high negative zeta potential (typically below –30 mV) ensures stable aqueous colloidal suspensions without the need for surfactants. This enables straightforward processing via methods like vacuum-assisted filtration, spin coating, and spray coating. MXene surface modification using cationic surfactants and polymers including PDMS, PVA, CTAB, and PEO has been widely explored for various membrane applications [53].

(d) Chemical Stability: One of the challenges in using $Ti_3C_2T_x$ MXene is its rapid degradation under ambient conditions due to the oxidation of titanium carbide into titanium dioxide (TiO_2), which significantly reduces its mechanical, electrochemical, and conductive properties. For example, exposure to air causes degradation rates of 42%, 85%, and 100% after 5, 10, and 15 days, respectively, largely due to the formation of anatase-phase TiO_2, which manifests as a cloudy-white colloid. Several strategies have been developed to improve MXene stability, including edge capping with polyphosphates (polyanionic salts), sodium ascorbate treatment, freeze storage at –80 °C and –20 °C, and the use of L-ascorbic acid. Additionally, refining the synthesis of Ti_3AlC_2 to a more stoichiometric MAX phase (Al-Ti_3AlC_2) has extended stability durations to 30, 80, 273, 650, 28, and 300 days, depending on the method used [54]. Other preservation techniques include storage in argon-filled containers at low temperatures, drying into films, embedding in polymer matrices, or annealing in a hydrogen atmosphere [53].

(e) Electrical Conductivity: The intrinsic metallic conductivity of some MXene structures provides a unique advantage in desalination technologies, where applied electric potentials can modulate ion transport across membranes. A notable study showcased the ability to control the permeation of salts such as $MgSO_4$ and NaCl through MXene-based membranes by alternating between positive and negative electrical voltages [55].

(f) Antimicrobial Properties: MXenes exhibit strong antibacterial properties, which are particularly valuable in membrane-based desalination to prevent biofouling. Whether dispersed in solution, coated on surfaces, or incorporated into polymer matrices, MXenes have demonstrated effective antimicrobial performance [53].

4. Fabrication of MXene-based desalination membranes and recent advances

Several advanced MXene-based membrane structures, including mixed-matrix membranes (MMMs), thin-film composites (TFCs), and nanolaminate membranes (NLMs), have been developed for desalination and wastewater treatment applications [56].

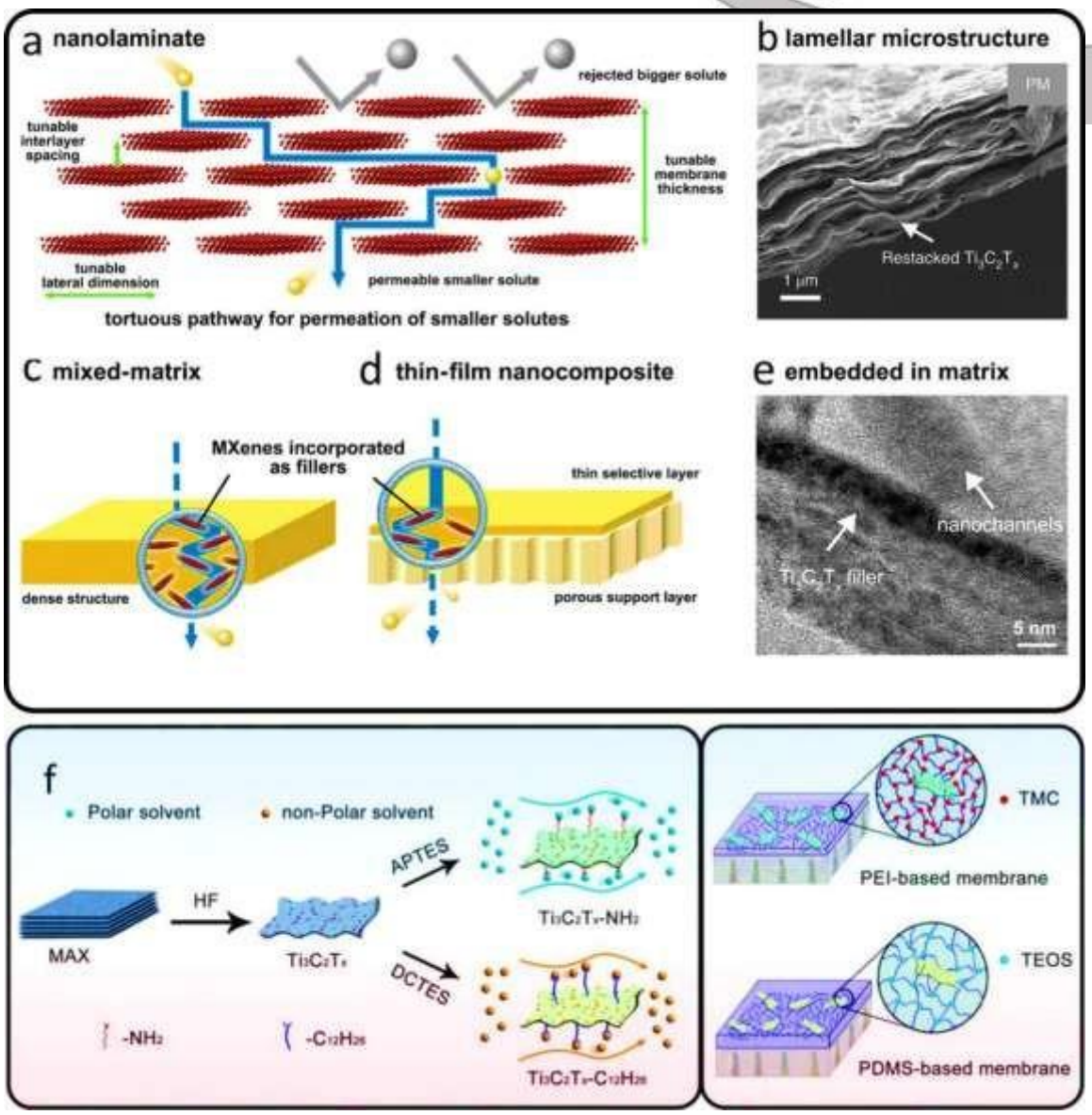


Fig. 4 (a) Schematic illustration of solute transport through an MXene-based NLM.

(b) Representative electron microscopy image of an MXene-based NLM. (c) Mixed matrix membranes (MMMs) prepared by incorporating MXene nanosheets into bulk polymer matrices. (d) Thin-film nanocomposite (TFN) membranes fabricated by embedding MXene nanosheets within thin selective layers on a porous support. (e) Representative microscopy image of an MXene nanosheet embedded within a polymer matrix. Reproduced with permission from Ref. [57]. (f) Synthesis process of $Ti_3C_2T_x$ and $Ti_3C_2T_x$-M, along with the microstructure of the composite membranes. Reproduced with permission from Ref. [58].

4.1 Mixed-Matrix Membranes (MMMs)

Mixed-matrix membranes are hybrid materials composed of polymer matrices integrated with nanomaterials, leveraging the strengths of both organic and inorganic components. In these systems, nanoparticles are dispersed within a continuous polymer phase, as illustrated in Fig. 4 c and d , to enhance membrane performance [59] [57]. For the successful fabrication of defect-free MMMs, key factors include strong compatibility between fillers and the polymer solution, stable dope solution properties, and robust membrane structure.

MXenes are particularly well-suited for MMMs due to their polar nature, hydrophilicity, and high surface morphology, which foster strong interfacial interactions with polymer chains [57]. Moreover, MXene materials such as $Ti_3C_2T_x$ display excellent dispersibility in a range of solvents, including water, ethanol, NMP, DMSO, and DMF [60]. Functionalizing the surface hydroxyl groups on $Ti_3C_2T_x$ MXenes can further improve compatibility and interface stability within the polymer matrix [58]. For instance, Ren et al. reported the development of $Ti_3C_2T_x$/PVA MMMs that exhibited enhanced mechanical strength and improved water flux [61].

4.2 Thin-Film Composite Membranes (TFCs)

TFC membranes typically consist of a dense selective polyamide (PA) layer formed atop a porous support layer. The PA layer is synthesized through interfacial polymerization (IP) involving two monomers typically an aqueous solution of m-phenylenediamine (MPD) and an organic solution of trimesoyl chloride (TMC). To improve membrane performance, nanomaterials such as MXenes, MOFs, or COFs can be incorporated into the aqueous MPD phase [62].

Using this approach, a novel TFC reverse osmosis (RO) membrane was fabricated by integrating $Ti_3C_2T_x$ MXene flakes into the selective layer. Various MXene loadings (0.005-0.02 wt%) were introduced into the MPD solution, followed by immersion of a polysulfone support in this modified solution. Subsequent treatment with a 1 wt% TMC solution led to the formation of thin-film nanocomposite (TFN) membranes. These membranes demonstrated improved surface hydrophilicity and reduced surface roughness. As a result, water flux increased from 1.73 to 2.53 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, with a high salt rejection rate of up to 98.5% [57]. In another study, Bolisetty et al. created laminated MoS_2-MXene nanocomposites through liquid exfoliation, incorporating them into the active layer of TFN membranes. The improvements in surface characteristics and reduced selective layer thickness significantly enhanced membrane performance [63].

4.3 Nanolaminate Membranes (NLMs)

Nanolaminate membranes are typically produced through pressure- or vacuum-assisted filtration techniques. In this process, MXene nanoparticles are dispersed in a suitable solvent to form a uniform suspension, which is then deposited onto a substrate to form the membrane layer [64, 65]. The performance of these membranes is influenced by various factors, including the substrate type, MXene flake size, their stacking orientation, solvent composition, drying conditions, membrane thickness, and tightness [66, 67].

Xu et al. utilized spin coating to fabricate MXene membranes on polyacrylonitrile substrates [68], while dip-coating was employed on ceramic Al_2O_3 supports [68]. Rheological studies have shown that the concentration of MXene colloids significantly affects their properties. For example, low concentrations of $Ti_3C_2T_x$ MXenes exhibit strong hydrophilicity and surface charge, resulting in high viscosity and partial elasticity. Increasing the concentration leads to pronounced viscoelastic behaviour [69]. Other fabrication techniques such as drop casting, vacuum-assisted filtration (VAF), and hot pressing are also commonly used for constructing MXene-based membranes, including MMMs, TFNs, and NLMs [56].

5. Mechanisms of Water desalination utilizing MXene membranes

This section elucidates the multifaceted mechanisms underpinning the efficacy of MXene membranes in water treatment applications. By exploring filtration processes, adsorption phenomena, and the influence of hydrophilicity, we aim to provide a comprehensive understanding of how these advanced materials operate.

5.1. Filtration Mechanisms: Size Exclusion and Charge Interactions

MXene-based membranes have emerged as promising candidates for water treatment applications, owing to their unique filtration behavior that combines size-based exclusion and electrostatic interactions. Their nanoscale interlayer spacing can be precisely adjusted, allowing for selective removal of contaminants according to molecular size. Additionally, the naturally occurring surface charges of MXenes facilitate strong interactions with charged species, leading to enhanced pollutant rejection. This combination of size selectivity and charge-based filtration highlights the versatile and efficient nature of MXene membranes, positioning them as a cutting-edge solution in modern water purification technologies.

5.2 Adsorption Dynamics of Pollutants on MXene Surfaces

The interaction dynamics between pollutants and MXene surfaces are crucial for their effectiveness in next-generation water purification systems. Recent studies emphasize the unique surface functionalities of MXenes, which not only offer high adsorption capabilities across a broad spectrum of organic and inorganic pollutants but also significantly contribute to enhancing membrane functionalities. The kinetics of pollutant uptake by MXenes are strongly governed by environmental

variables, including pH levels, ionic strength, and the presence of competing ions. Therefore, understanding these parameters is essential for fine-tuning operating conditions and improving overall treatment performance. Such insights facilitate the development of customized MXene-based membrane systems capable of delivering high-efficiency water purification.

Two types of nanosheets porous and non-porous can be assembled to create two-dimensional (2D) membranes. Porous nanosheets, such as those found in zeolite-based membranes, metal–organic framework (MOF) membranes, and covalent organic framework (COF) membranes, consist of one or more layers with precisely defined nano or sub-nanoporous structures that allow selective molecular transport (Fig. 5a). Conversely, non-porous 2D materials like graphene oxide (GO), layered double hydroxides (LDHs), MXenes, and transition metal dichalcogenides (TMDs) rely on the orderly stacking of nanosheets to form interlayer nanochannels that serve as selective transport pathways (Fig. 5b). Specifically, for MXene-based membranes, molecular separation occurs via three primary mechanisms: size exclusion, adsorption, and electrostatic repulsion (Fig. 5c) [70] [71].

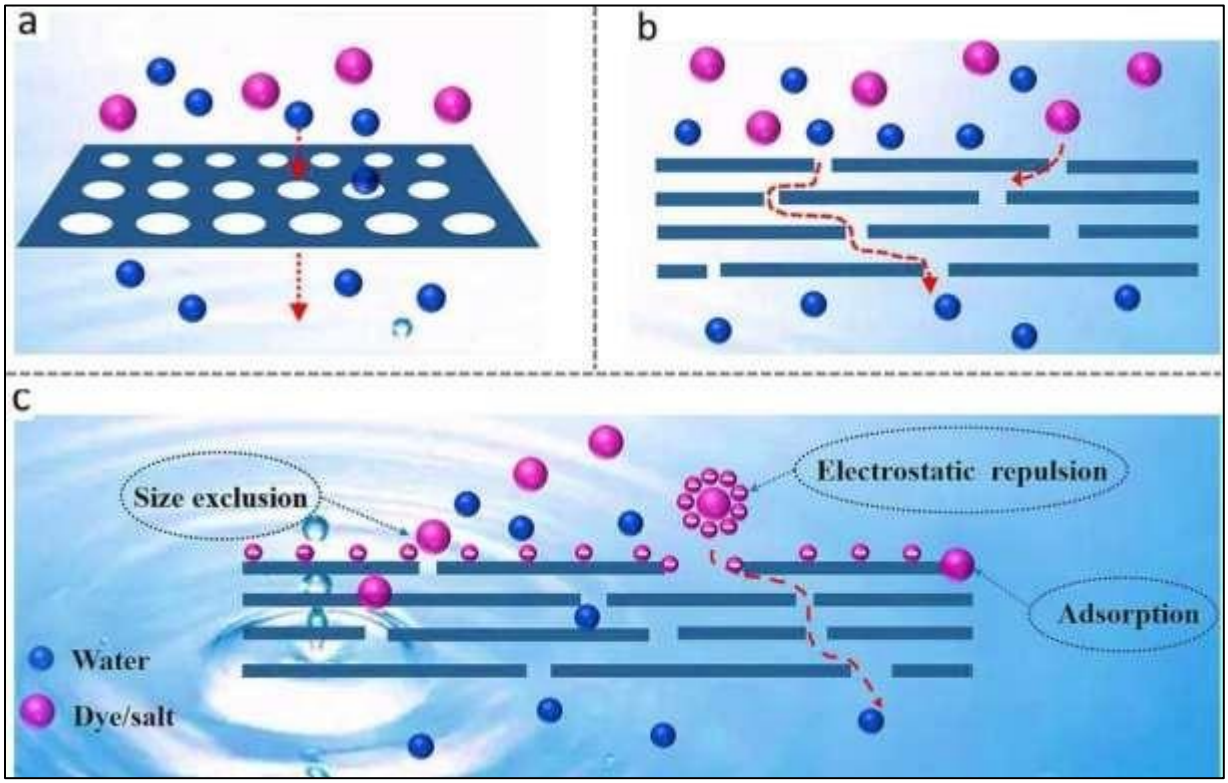


Fig. 5 Schematic of the two types of 2D material membrane.

(a) Porous nanosheets membrane and (b) laminar membrane. (c) Three separation mechanisms of 2D MXene membranes. Adapted with permission from Ref. [70].

Stacked MXene nanosheets form membranes with precise interlayer spacings, typically ranging from 1 to 1.5 nm, as determined by microscopic analysis and Bragg's equation [72-74]. These narrow interlayer gaps are considerably smaller than the size of many pollutants, such as oil–water emulsion droplets and various dye molecules. Thus, MXene membranes effectively exclude larger molecules based on the size-sieving principle.

Electrostatic interactions also significantly influence membrane separation behavior. Due to the Donnan exclusion effect, negatively charged MXene surfaces repel similarly charged species while attracting oppositely charged ions [75]. Ren et al. demonstrated that multivalent cations such as Mg^{2+}, Ca^{2+}, and Al^{3+} can compress MXene layers through strong electrostatic interactions, thereby reducing ion transport. In contrast, monovalent ions like Na^{+} can slightly swell the membrane by forming bi-layered structures on either side of the MXene lamellae, which enhances permeation [76].

Surface functional groups on MXenes play a key role in the selective rejection of ions and molecules. These groups may interact through electrostatic forces, π–π interactions, or metal-ligand coordination, thereby either facilitating or hindering transport through the membrane. This adsorption-driven mechanism complements the size-exclusion effect. Among these mechanisms, size exclusion is generally the most dominant for rejecting molecules larger than 2.5 nm through the well-defined channels in MXene-based membranes. For example, membranes tested with dyes such as Rhodamine B, methylene blue, methyl orange, and Congo red demonstrated rejection rates exceeding 95%, regardless of dye charge [77-79].

While the Donnan effect contributes to the overall ion exclusion efficiency, its role is supplementary. According to the Donnan exclusion principle, ions sharing the same charge as the membrane are electrostatically repelled to maintain electroneutrality. As a result, even solutes smaller than the interlayer gaps can be rejected due to charge-based exclusion [80]. Hence, negatively charged dyes tend to be rejected more effectively by MXene membranes than positively charged counterparts [77-79].

Adjusting the interlayer spacing in MXene laminates, typically within the nanometer to sub-nanometer scale, enables selective separation of small molecules. This makes MXene-based membranes particularly suitable for purifying both aqueous and organic solutions. The flow of solvents through these membranes can be described by the Hagen–Poiseuille (H–P) equation [80, 81]:

$$\text{Flux} = \frac{-h_d^4 \Delta p}{12 l^2 \eta_s \Delta x}$$

Here, h_d represents interlayer spacing, Δp is the transmembrane pressure, l is the lateral size of MXene flakes, η_s is the solvent viscosity, and Δx is the membrane thickness. According to this relation, increasing h_d (interlayer spacing) and decreasing l (nanosheet size) enhance solvent flux. Introducing intercalants into MXenes is one strategy to expand these interlayer channels. However, steric hindrance from intercalants may compromise selectivity even as permeability improves[19, 82]. Therefore, to boost water flux without reducing rejection efficiency, supplementary modification techniques are required. Fabricating thinner membranes with more direct pathways can shorten diffusion distances and increase permeability. Additionally, modifying surface charges and chemical groups on MXenes provides another route for controlling interlayer spacing and optimizing mass transport.

6. MXene Membranes in desalination Applications

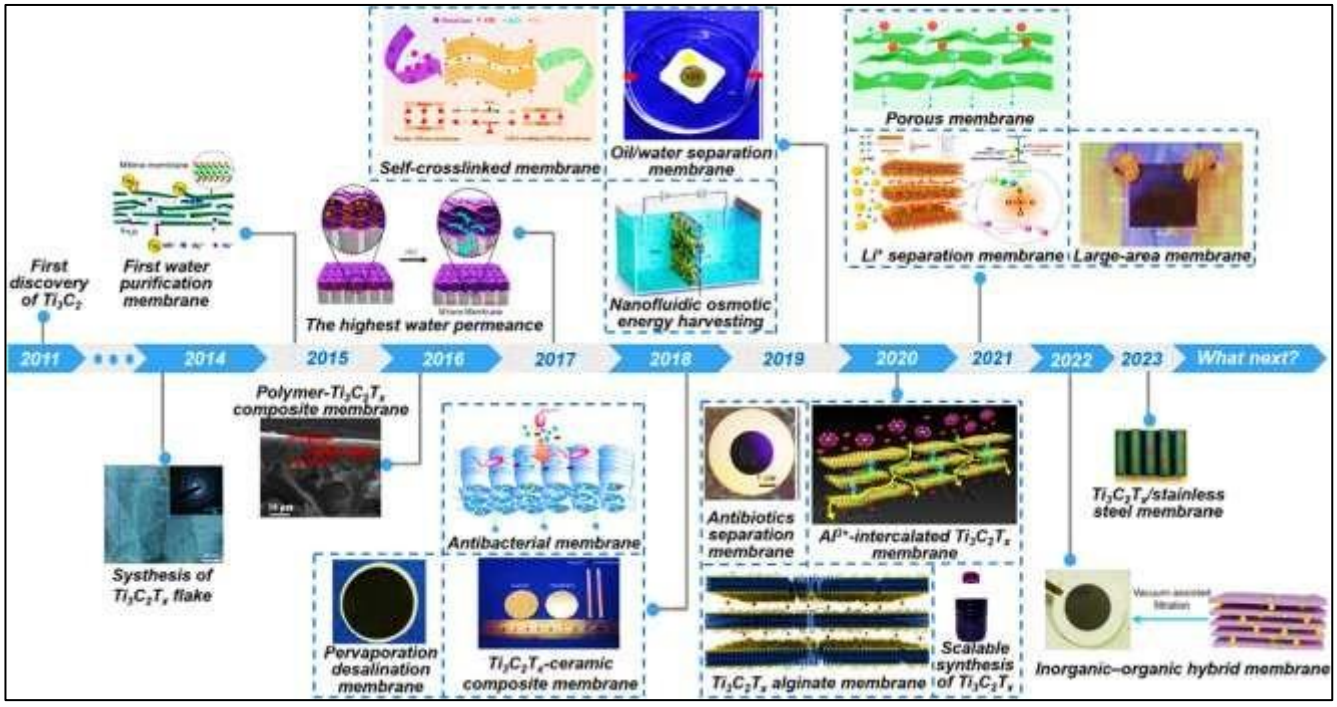


Fig. 6 Historical Progress and Key Advances in MXene Membrane Development. Reproduced with permission from Ref. [83].

Membrane-based separation and purification technologies are extensively employed in industries such as chemical processing, pharmaceuticals, and water treatment, owing to their numerous benefits. These include a reduced carbon footprint, high reliability, operational simplicity, and minimal secondary pollution [84]. Depending on the nature of the contaminants, various filtration and separation techniques are applied for water treatment. As depicted in Fig. 6a, Sun et al. [83] present a historical overview of MXene-based membrane development (primarily $Ti_3C_2T_x$) [85].

Key principles for fabricating MXene-based membranes emphasize efficient separation capabilities, long-term operational stability, and sustainable production practices. These aspects are largely governed by the dispersibility, hydrophilicity, and stability of MXene materials [86].

MXenes are incorporated into membranes via two main strategies. The first involves fabricating membranes entirely from MXene particles, while the second embeds MXene particles within an existing polymeric membrane matrix. For the former, MXene particles are typically dispersed in solution and deposited onto a supporting layer through filtration. For example, Han et al. [87] prepared a $Ti_3C_2T_x$ solution, which was then filtered over a polyethersulfone ultrafiltration (UF) membrane in a dead-end setup under 0.2 MPa pressure with constant stirring. The resulting membrane had a surface area of 48 cm^2. Altering the concentration of MXene significantly impacted the membrane's morphology and filtration performance.

Notably, a straightforward self-assembly method using negatively charged $Ti_3C_2T_x$ nanosheets and positively charged alumina (Al_2O_3) nanoparticles was achieved with mild etchants like HCl and LiF [20]. A membrane with a 1:1 mass ratio of MXene to Al_2O_3 demonstrated a water permeability of 88.8 LMH/bar approximately four times higher than that of pure Al_2O_3 membranes and showed over 99.5% rejection of Rhodamine B and Methylene Blue, as further detailed in the nanofiltration (NF) section.

In the second approach, MXenes especially $Ti_3C_2T_x$ are integrated within polymer membranes. This can take the form of mixed matrix membranes (MMMs), typically used in ultrafiltration, or thin-film nanocomposite (TFN) membranes, commonly employed in reverse osmosis (RO) [53]. Additionally, a variety of other fabrication methods have been utilized, including pressure-assisted filtration, layer-by-layer assembly, and dip-, spray-, and spin-coating techniques [88].

For scaling up, large-area deposition methods such as slot-die coating and electrophoretic deposition have also been explored [83]. However, MXenes are susceptible to oxidation in aqueous environments, which can affect their performance and structural integrity. Compared to oxidized forms, MXenes terminated with –F and –OH groups exhibit enhanced conductivity and stronger plasmonic responses to light. Raman analysis using a low-power 532 nm laser revealed that oxidation-induced structural changes in MXenes become evident at laser powers above 5 mW. Degradation of the film was notable at 1.5 MW/cm^2 and intensified at 17 kW/cm^2. Raman spectra indicated the emergence of strong G and D bands, associated with graphitic and amorphous carbon, as well as TiO_2 in its anatase phase implying oxidation of Ti to TiO_2 accompanied by carbon structure formation [89]. Raman measurements at 532 nm and 633 nm excitation wavelengths confirmed these transformations, and vibrational bands at higher energies reflected structural disorder and non-uniformity in the MXene films. Specific wavenumbers helped identify $Ti_3C_2T_x$ lattice modes terminated with different functional groups. The appearance of graphene-like bands signaled oxidation and disruption of the MXene lattice.

Furthermore, solution pH plays a crucial role in surface chemistry; lower pH levels (higher hydrogen ion concentrations) promote hydroxyl group termination on MXene surfaces. Protonation under acidic conditions may impart a slight positive charge to MXene layers, influencing their interactions and behavior [90]. While the application of $Ti_3C_2T_x$-based membranes is discussed in subsequent sections, it is important to note that microfiltration (MF) processes are not covered due to the lack of substantial evidence supporting their use in this specific context.

6.1. Ultrafiltration

Ultrafiltration (UF) is widely utilized in water treatment due to its operational simplicity and effectiveness. Despite its advantages, membrane fouling remains a persistent challenge [91]. Compared to nanofiltration (NF) and reverse osmosis (RO) membranes, UF membranes operate at lower pressures, making them a cost-efficient solution for tasks such as removing residual powdered substances from feedwater. To improve the antifouling performance, MXenes have been integrated into UF membranes either by direct fabrication or via in-situ incorporation during the phase inversion process. This addition enhances membrane hydrophilicity, as shown by reduced water contact angles. Rasool et al. [92] reported that while unmodified polysulfone membranes had a bovine serum albumin (BSA) rejection rate of 77.48%, MXene-modified membranes consistently exceeded 90% rejection.

Increasing MXene concentration resulted in improved reversible fouling behavior and better flux recovery. For example, depositing 2–6 mg of $Ti_3C_2T_x$ nanosheets onto a polyvinylidene difluoride (PVDF) substrate (47 mm diameter) produced membranes of varying thickness (0.6–1.8 mm). Initially, the PVDF substrate exhibited a water contact angle of 81°, indicating

hydrophobicity. After coating with $Ti_3C_2T_x$, the contact angle dropped to 37°, confirming a significant increase in surface hydrophilicity [64]. Furthermore, as MXene loading increased, membrane surface roughness and thickness decreased. This trend was attributed to the accumulation of MXene in the active upper layers, enhancing density and facilitating more efficient water-solvent exchange during phase inversion a process strongly influenced by MXene's hydrophilic nature [86].
Zhou et al. proposed a mechanism by which $Ti_3C_2T_x$ is embedded within the polymeric matrix [93]. The hydrophilicity of $Ti_3C_2T_x$ facilitates water transport by forming hydrogen bonds, accelerating phase inversion, reducing skin layer thickness, and generating more macro voids. The nanosheets' thin and hydrophilic structure also allows for minimal doping content while still improving membrane porosity. Fig. 7 from Zhou et al. [93] illustrates the phase inversion process with and without $Ti_3C_2T_x$ doping in a polysulfone (PSE) casting solution. Remarkably, even a small addition of $Ti_3C_2T_x$ significantly enhanced the rate of phase separation and porosity.

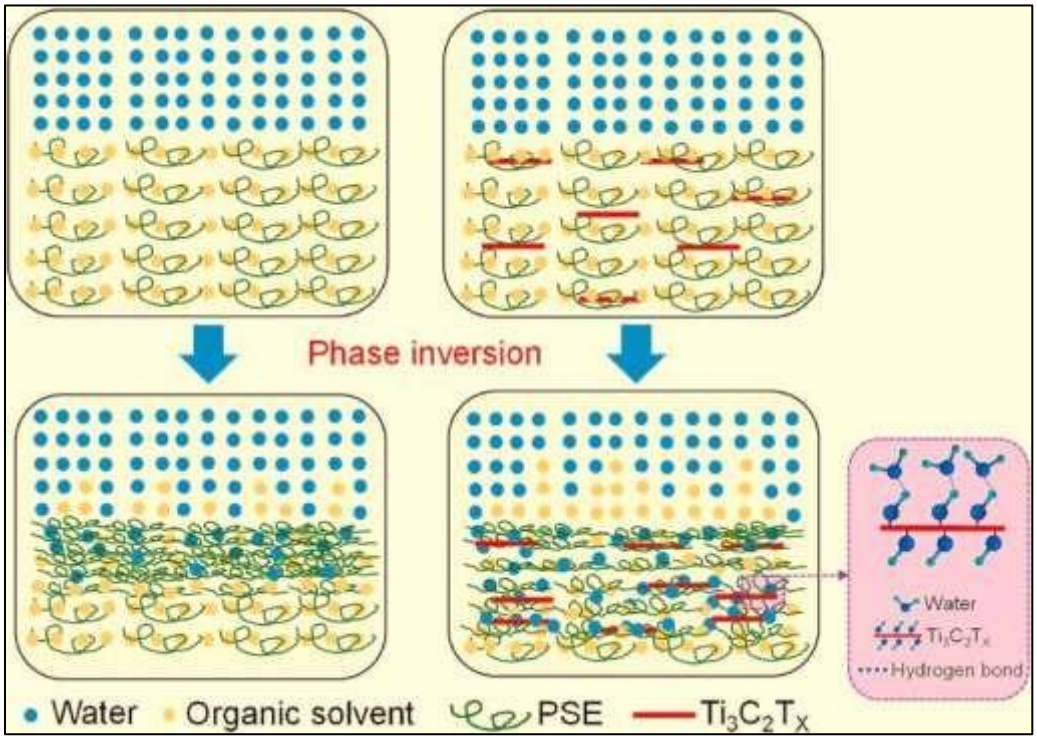


Fig. 7 Schematic representation of the phase inversion mechanism in PSE casting solutions with and without $Ti_3C_2T_x$ nanosheet incorporation. The introduction of a trace amount of $Ti_3C_2T_x$ nanosheets significantly promotes the phase inversion kinetics, resulting in faster demixing and the formation of membranes with enhanced porosity. Reproduced with permission from Ref. [93].

In a different strategy, pure 2D Ti_2CT_x MXene membranes were fabricated [74] by incorporating hyperbranched polyethyleneimine (PEI) into an anodic aluminum oxide (AAO) substrate with 100 nm pores, aiming to improve solvent dehydration [94]. Despite the structured MXene layers, some in-plane non-selective pores remained, potentially impairing membrane efficiency [95]. To address this, a direct interfacial polymerization approach was employed, where trimethyl chloride reacted with the PEI in the membrane to seal these defects effectively [74].
MXene-based UF membranes have also been applied in dye removal from water [96]. Their morphological and textural properties were analyzed using SEM, TEM, BET surface area analysis, XRD, and pore size distribution. To evaluate performance, both MXene-UF and PAC-UF systems were tested using synthetic wastewater containing methylene blue (MB) and methyl orange (MO) dyes. MXene-UF exhibited superior normalized flux values (0.90 for MB and 0.92 for MO) compared to PAC-UF (0.72 for MB and 0.75 for MO) and unmodified UF membranes (0.86 for MB and 0.90 for MO). The integration of adsorbents helped reduce irreversible dye fouling more effectively than UF alone.
To enhance both antifouling resistance and permeability, $ZnFe_2O_4$-MXene composites were synthesized using a coprecipitation method and embedded into PES-based membranes to form mixed-matrix membranes (MMMs) [97]. The bimetallic $ZnFe_2O_4$ particles facilitated better dispersion of MXene within the PES matrix and improved interfacial

compatibility, both on the surface and between MXene layers. The hydrophilic functional groups on $ZnFe_2O_4$-MXene composites further enhanced the membrane's hydrophilicity, pore architecture, and surface polarity.

6.2. Nanofiltration

Nanofiltration (NF) is widely recognized for its efficiency in removing dyes and large ions from water, attributed to its low energy requirements, environmental friendliness, and high separation performance. Beyond traditional thin-film composite (TFC) membranes, researchers have explored various advanced materials to enhance NF performance. Since the isolation of monolayer graphene in 2004, a broad array of two-dimensional (2D) nanomaterials such as graphitic carbon nitride (g-C_3N_4), graphene oxide (GO), MXene, and metal-organic frameworks (MOFs) has emerged as promising candidates for membrane fabrication [98, 99].

These 2D materials not only outperform polymeric membranes in terms of chemical and thermal stability but also offer rapid and selective water transport. This is due to their well-aligned interlayer channels and high density of nanopores [100]. Compared to polymers, their superior resilience under harsh operating conditions makes them particularly suitable for NF applications [101, 102]. Among these, MXenes have gained considerable attention in recent years due to their outstanding structural and surface characteristics [103].

In one study, $Ti_3C_2T_x$ nanosheets were incorporated into aramid nanofiber (ANF) membranes to tailor molecular weight cutoffs and enhance dye/salt separation capabilities [104]. A composite membrane with 20 wt% MXene content demonstrated strong rejection rates for dyes approaching 99% for Alcian Blue, 98% for Rose Bengal, and 94% for Congo Red while allowing minimal NaCl rejection (0.2%) at a salt concentration of 5 g/L, all without compromising water permeability.

Another approach involved the stacking of MXene nanosheets in interlayers to form thin-film nanocomposite interlayer (TFNI) membranes. Here, Fe_3O_4 nanoparticles were used as sacrificial spacers to tune the channel spacing between layers. Compared to standard TFC membranes, this configuration resulted in thinner, more hydrophilic, and rougher polyamide layers. The modified membranes showed nearly double the water flux and achieved a higher selective separation factor of 48.4, while maintaining salt rejections above 97% [105].

A hybrid membrane composed of GO and MXene (referred to as GM) was developed via a simple vacuum-assisted assembly method [78]. By varying the MXene content, researchers studied changes in structural attributes, solvent permeability, and dye rejection. The resulting GM membranes demonstrated excellent flux values 21.02, 48.32, 25.03, 10.76, and 6.18 $L \cdot m^{-2} \cdot h^{-1}$ for water, ethanol, methanol, acetone, and isopropanol (IPA), respectively, under 0.5 bar pressure. They also showed dye rejection rates exceeding 90% in both aqueous and organic media.

Additionally, a self-assembly-based nano-intercalation strategy enabled the formation of MXene membranes with tailored internal structures and surface properties [20]. Structural tuning and filtration performance were studied in detail across different dye and salt solutions. With an optimal MXene/Al_2O_3 mass ratio of 1:1, the membrane achieved water permeability as high as 88.8 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ four times that of pristine MXene membranes while ensuring dye rejection efficiencies greater than 99.5% for methylene blue (MB) and rhodamine B (RhB). This enhancement was attributed to the improved interlayer spacing and channel stability offered by nano-Al_2O_3 intercalation.

Another innovative design incorporated silver nanoparticles (AgNPs) into the $Ti_3C_2T_x$ MXene layers, forming a membrane with high water flux and operational durability [106]. The membrane, crosslinked with hyperbranched polyethyleneimine (HPEI), maintained consistent water permeability between 24.64 and 30.73 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ and provided nearly complete dye rejections (>99%) for MO, CR, RhB, and MB. For salt solutions, the membrane showed promising nanofiltration performance with rejection values of 84.15% for $MgSO_4$, 77.01% for $MgCl_2$, 74.67% for Na_2SO_4, and 56.58% for NaCl.

The underlying separation mechanisms of MXene-based NF membranes include a combination of electrostatic repulsion, size sieving, the Donnan effect, and steric hindrance. For example, negatively charged MXene membranes typically repel similarly charged dye molecules, while positively charged variants like HPEI-AgNP@$Ti_3C_2T_x$ membranes exhibit different interactions. The lowest rejection occurs for small negatively charged molecules, and moderate rejection for larger positively charged ones, indicating a synergistic role of charge repulsion and molecular size exclusion. In salt filtration, positively charged membrane surfaces repel cations and attract anions to maintain electrical neutrality, a phenomenon explained by the Donnan effect combined with steric hindrance. These synergistic mechanisms contribute to the high selectivity and performance of MXene-based NF membranes.

6.3. Reverse osmosis

Reverse osmosis (RO) membranes are widely regarded for their excellent separation capabilities and ease of use, making them a leading choice for water desalination applications [107]. The incorporation of MXene into polyamide thin-film membranes is being explored as a strategy to enhance RO membrane performance, aligning with the broader trend of using additives to improve membrane properties [108]. Among various RO technologies, thin-film composite (TFC) membranes are especially critical in desalination and water reclamation due to their superior structure and function. The growing interest in nanomaterials across multiple sectors including water purification is driven by their notable characteristics, such as enhanced permeability, selectivity, chemical stability, and lower susceptibility to fouling [109].

TFC membranes are particularly advantageous over conventional RO membranes, offering high water permeability, excellent salt rejection efficiency, and durability under a wide range of pH and pressure conditions [110]. Despite their high performance, TFC membranes remain cost-effective, which contributes to their widespread use and limits the viability of alternative technologies [111].

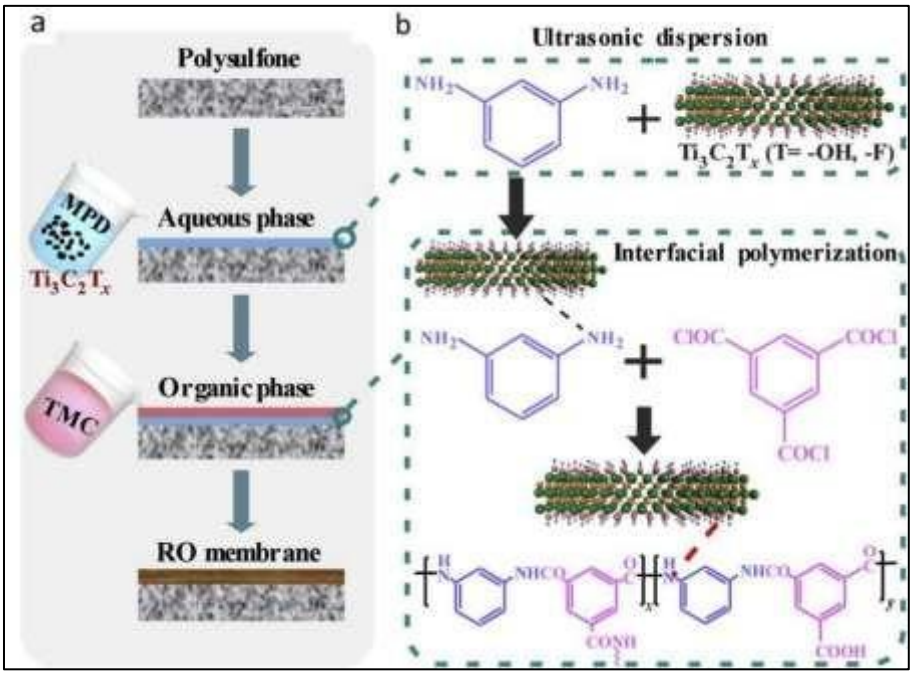


Fig. 8 (a) Schematic representation of the fabrication process for $Ti_3C_2T_x$-incorporated polyamide reverse osmosis (RO) membranes.

(b) Illustration of the interfacial polymerization mechanism. Reproduced with permission from Ref. [111].

In recent developments, polyamide RO membranes have been fabricated using an in-situ interfacial polymerization method, incorporating small amounts (0% to 0.02% by mass) of two-dimensional $Ti_3C_2T_x$ nanosheets. The addition of these layered nanomaterials has been shown to significantly improve surface hydrophilicity while simultaneously decreasing surface roughness. As a result, water permeability improved substantially from 1.74 to 2.53 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ without compromising the membrane's salt rejection capability [112].

7. Fouling resistivity performance

Membrane fouling continues to be one of the major obstacles limiting the efficiency and long-term performance of water desalination processes, especially in reverse osmosis (RO) and nanofiltration (NF) systems. The accumulation of undesirable foulants such as proteins, lipids, microorganisms, and inorganic particulates on membrane surfaces or within pores leads to reduced efficiency, diminished water quality, increased operational costs, and shorter membrane lifespans. In recent years, MXene-based materials have attracted growing interest in the development of fouling-resistant membranes due to their intrinsic antibacterial activity and tunable surface properties.

The surface characteristics of membranes, including hydrophilicity, roughness, and surface chemistry, are key parameters influencing fouling behavior. MXenes, especially $Ti_3C_2T_x$, have demonstrated promising antifouling capabilities by deterring

the adhesion of organic matter, microbial organisms, and inorganic salts. Functionalization of MXene surfaces with hydrophilic terminal groups (e.g., –OH, –O, –F) enhances their water affinity and minimizes interactions with organic foulants. Additionally, the presence of hydroxyl and carboxyl groups contributes to improved resistance against biofouling by inhibiting bacterial adhesion.

Surface roughness on the nanoscale can further bolster antifouling performance, as increased roughness may reduce the effective contact area between foulants and the membrane surface. Moreover, incorporating nanoparticles within MXene matrices enables the formation of hybrid structures that further suppress the adhesion of particulate contaminants [111]. Wang et al. [111] evaluated the antifouling properties of polyamide (PA)-$Ti_3C_2T_x$ membranes using bovine serum albumin (BSA) as a model protein foulant. Their findings revealed that modifications to membrane hydrophilicity, surface potential, and roughness significantly reduced protein adhesion. The PA15 membrane, enriched with $Ti_3C_2T_x$, exhibited fewer surface-deposited foulants compared to the unmodified PA membrane after six hours of exposure, as evidenced by SEM imaging (Figure 9a I–III).

Humic acid (HA), a prevalent organic foulant, is particularly challenging due to its irreversible fouling behavior and synergistic interactions with metal ions, which aggravate membrane degradation. Vatanpour et al. [113] investigated TFC RO membranes blended with quasi-MXene materials and observed improved antifouling resistance during filtration of HA/NaCl mixtures. Enhanced hydrophilicity confirmed by contact angle analysis contributed to this improvement. The antifouling behavior was attributed to multiple factors: hydrophilic repulsion between Ti_2NT_x and HA, electrostatic interactions, and HA adsorption onto the MXene-modified surfaces.

Huang et al. [114] developed a TiO_2@MXene-enhanced polyethersulfone (PES) membrane with notable resistance to a variety of foulants, including sodium alginate (SA), BSA, HA, and yeast. The antifouling mechanism was elucidated via XDLVO theoretical calculations, revealing that increased electron donor characteristics led to stronger repulsive interactions with negatively charged foulants, validating the membrane's antifouling potential.

A unique approach was presented by Zhang et al. [115], who engineered a polyvinylidene fluoride-ZnO/MXene (PVDF-ZM) membrane capable of reversible switching between hydrophobic and hydrophilic states. In its superhydrophobic state, the membrane creates an air barrier that inhibits direct contact between seawater and the membrane surface, preventing foulant deposition. Upon UV irradiation, the membrane transitions to a hydrophilic state, reducing adhesion forces and allowing for easy removal of accumulated foulants. After cleaning, the surface reverts to its original superhydrophobicity, demonstrating self-healing properties. Post-cleaning flux recovery reached 93.4% and 97.9% for BSA and HA, respectively (Fig. 9b).

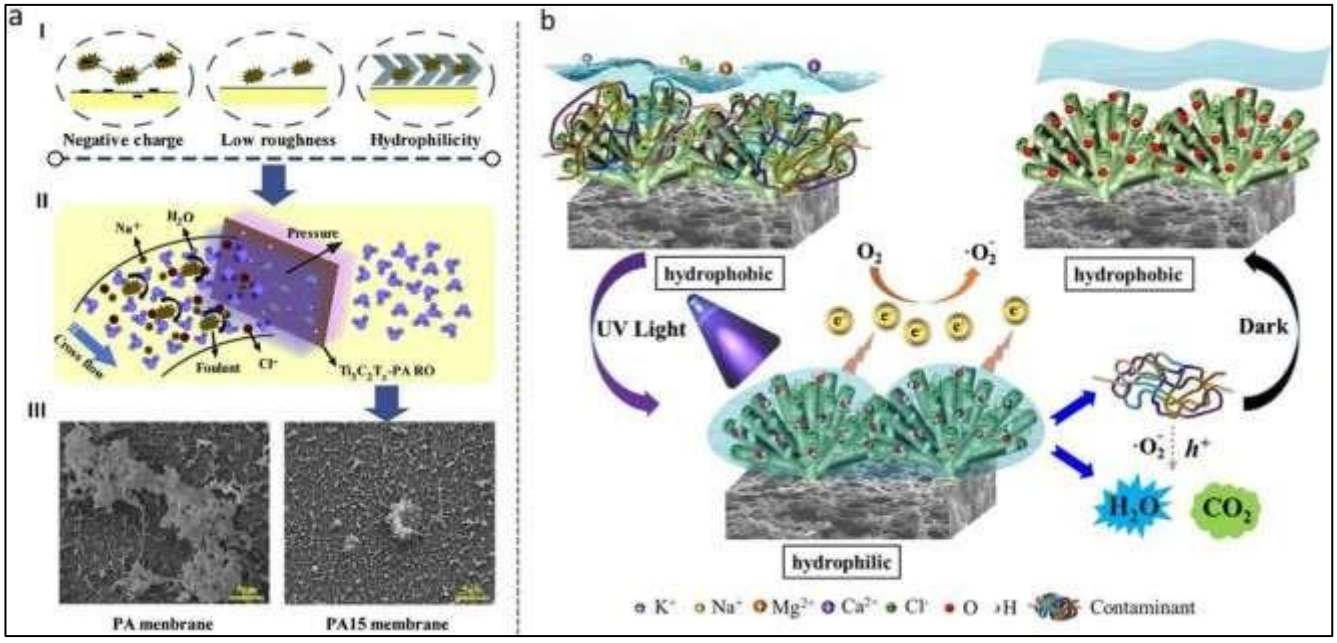


Fig. 9. (a) **(I) Mechanisms underlying the superior fouling resistance of the PA–$Ti_3C_2T_x$ reverse osmosis membrane.**

(II) Diagram depicting the desalination process together with the anti-fouling mechanism; (III) SEM images showing the surface morphology of PA and PA15 membranes after fouling assessment. Reproduced with permission from Ref. [111]. (b) Schematic illustration of the self-recovery mechanism of the PVDF-ZM membrane through a reversible hydrophilic-to-hydrophobic transition. Reproduced with permission from Ref. [115].

Inspired by bio-functional strategies, Luo et al. [116] introduced a straightforward method to functionalize MXene ($Ti_3C_2T_x$) with amino acids such as glycine (Gly), L-lysine (L-Lys), L-cysteine (L-Cys), and L-glutamic acid (L-Glu). These modifications adjusted the surface charge and interlayer spacing of MXene, enhancing antifouling performance. Notably, the Gly-modified membrane demonstrated nearly twice the flux recovery ratio (FRR) compared to pristine MXene when tested with 1000 ppm BSA, indicating superior resistance to protein fouling.

Zarshenas et al. [117] proposed an environmentally friendly and cost-effective strategy for enhancing membrane performance by coating $Ti_3C_2T_x$ with plant-derived polyphenol tannic acid (TA). The modified $Ti_3C_2T_x$–TA nanosheets were then incorporated into a polyamide thin-film nanocomposite RO membrane. This approach improved membrane hydrophilicity and introduced strong surface charges, promoting compatibility with the polyamide matrix and creating selective interfacial pathways for water transport. The TA functionalization also supported hydrogen bonding, which facilitated water diffusion and enhanced salt rejection and antifouling efficiency.

8. Comparative Analysis with Traditional Membrane Technologies

In membrane-based water desalination, two critical performance parameters are water permeability (or flux) and selectivity. Water permeability determines how effectively a membrane can transport water molecules, while selectivity reflects the membrane's ability to discriminate between water and dissolved solutes, such as sodium and chloride ions. An ideal membrane allows water to pass through while effectively rejecting salts and other impurities. Achieving high levels of both permeability and selectivity is essential for producing potable water from saline sources in an energy-efficient manner. However, a fundamental limitation in membrane design is the well-recognized permeability–selectivity trade-off, wherein an increase in water flux often comes at the expense of ion rejection efficiency, and vice versa. Overcoming this trade-off remains a significant challenge for the practical application of synthetic membranes. Enhancing both parameters simultaneously is therefore a primary objective in the development of mixed matrix membranes (MMMs) for broader industrial implementation.

Cellulose acetate (CA) symmetric membranes have been utilized in desalination applications since the 1960s. Their performance saw a notable improvement with the development of asymmetric membrane structures [118]. For instance, incorporating chitosan into a CA-based casting solution led to an increase in salt rejection from 81.5% to 92.3%, along with enhanced antibacterial properties. However, this modification also resulted in a reduction in membrane flux [119]. Despite their early promise, membranes fabricated from a single polymer such as CA are prone to limitations including compaction under high pressure, leading to reduced permeability, and susceptibility to hydrolysis under extreme pH conditions [120]. These drawbacks were effectively addressed with the advent of thin-film composite (TFC) membranes, particularly those based on polyamide (PA). Unlike single-polymer systems, TFC membranes offer an improved balance between selectivity and permeability, making them the benchmark for commercial desalination technologies.

Nevertheless, TFC membranes are not without limitations they tend to reach a performance ceiling, are vulnerable to fouling, and can degrade chemically over time. These challenges have stimulated the search for alternative membrane materials with improved durability and performance. In this context, inorganic membranes, traditionally made from metal oxides, have garnered attention. More recently, advances in nanostructured inorganic membranes have been reported, offering several technical advantages over polymeric counterparts. Key advantages include a narrow and homogeneous pore size distribution, enhanced porosity, high water permeance coupled with efficient separation, and exceptional mechanical, chemical, and thermal durability, making these membranes suitable for operation under severe conditions, including repeated chemical cleaning. [121]. Additionally, their intrinsic hydrophilicity contributes to reduced fouling tendencies.

Despite these advantages, the practical implementation of ceramic and inorganic membranes in full-scale desalination remains limited. Performance under real-world conditions often falls short of theoretical expectations. Moreover, they exhibit the common trade-off between water permeability and salt rejection, and their fabrication can be economically challenging. Currently, these membranes are more commonly used in hybrid systems, particularly as pretreatment stages in combination with oxidative processes to enhance the lifespan and efficiency of downstream polymeric membranes.

Thin-film composite (TFC) membranes have garnered substantial global interest due to their commercial viability, prompting extensive research aimed at enhancing their performance. One key strategy involves the development of mixed matrix membranes (MMMs), wherein nanomaterials are either embedded within the membrane matrix during fabrication or applied as surface coatings. Recent work by Jianwei Di et al. [122] has delved into the structure–performance correlation of polyamide (PA) membranes, highlighting innovative designs such as tunable crosslinked networks, crumpled morphologies, ultrathin selective layers, and the integration of additional permselective pathways.

Among the diverse range of nanomaterials explored for membrane enhancement are silver, copper, silica, and titanium dioxide nanoparticles. These efforts have expanded to include a unique class of materials known as two-dimensional (2D) materials, which are especially suited for desalination applications due to their exceptional characteristics including high aspect ratios, atomic-level thickness, robust mechanical properties, and intrinsic flexibility. This class of materials includes graphene and its related derivatives, hexagonal boron nitride (h-BN), elemental two-dimensional materials such as borophene, transition metal dichalcogenides (TMDs) including molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2), two-dimensional nanosheets derived from metal–organic frameworks (MOFs) and covalent organic frameworks (COFs), as well as the recently developed family of transition metal carbides and nitrides known collectively as MXenes. [123].

These 2D materials exhibit remarkable membrane performance by enhancing permeability, salt rejection, and resistance to fouling, while also offering superior mechanical and thermal stability compared to traditional polymer-based membranes. Comparative analyses have shown that membranes incorporating such nanomaterials can achieve water flux rates up to 84.7 $L/m^2 \cdot h$ under standard conditions, significantly outperforming conventional membranes, which typically yield fluxes in the range of 25–30 $L/m^2 \cdot h$ [124].

Within this context, MXenes have emerged as particularly promising candidates, frequently benchmarked against graphene oxide (GO) [125-129], MOFs [130-134], and MoS_2 [135-139] all of which are widely studied 2D materials in membrane-based desalination. Each of these materials offers distinct advantages and limitations. However, MXenes stand out for their structural adaptability, including tunable interlayer spacing and diverse surface functionalities, attributes that are less pronounced in GO due to its rigid and tightly bonded layers [140]. For instance, Ren et al. [141] demonstrated that MXene-based membranes outperformed GO in the selective removal of multivalent cations.

MOF nanosheets, though effective, pose challenges in terms of alignment, defect-free integration, and large-scale production, which limit their scalability [142]. In contrast, MXenes disperse easily in aqueous media and can be processed into films or polymer composites using scalable methods. Additionally, MOF membranes often suffer from structural degradation or loss of crystallinity under reverse osmosis (RO) operating conditions, whereas crosslinked or hybridized MXene membranes exhibit enhanced chemical and mechanical stability in aqueous environments [143].

Similarly, MoS_2's intrinsic hydrophobicity limits its interaction with water, necessitating surface functionalization or the addition of hydrophilic groups to achieve wettability comparable to that of MXenes [144]. The superior wettability, processability, and tunability of MXenes collectively contribute to their competitive edge among emerging 2D membrane materials. A comparative performance analysis, focusing on membranes tested under identical conditions specifically with flux values normalized to $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ and salt concentrations standardized at 1000 ppm is illustrated in Figure 18, showcasing the performance trade-offs across these nanomaterials.

MXene-based membranes exhibit remarkably high water permeance due to their intrinsic hydrophilicity, tunable interlayer spacing, and well-aligned lamellar nanochannel architecture, outperforming many other two-dimensional (2D) membrane materials in terms of permeability. However, despite these advantageous properties, their performance in salt rejection remains suboptimal for practical desalination applications. This limitation highlights the need for further structural refinement and surface functionalization to enhance their ion sieving efficiency and selectivity. For successful commercialization in seawater desalination, membranes typically require salt rejection rates exceeding 90% and a water flux in the range of 30–50 liters per square meter per hour (LMH).

9. Conclusion and Future Directions

MXenes, have emerged as a new frontier in membrane-based water purification, advancing the membrane technology to mitigate the escalating global challenges of water scarcity and contamination. As pressure mounts on existing freshwater sources due to industrialization, climate change, and population growth, innovative materials like MXenes are being recognized for their superior structural and surface properties ranging from high hydrophilicity and tuneable surface terminations to excellent ion sieving and mechanical stability. These features position MXenes as high-performance candidates for integration into next-generation membranes, applicable in technologies such as ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD).

Despite their demonstrated benefits, several challenges must be overcome to enable the scalable and sustainable use of MXenes in real-world water treatment systems. Among the primary concerns is the reliance on hazardous etchants like hydrofluoric acid (HF) in traditional synthesis routes. The development of environmentally friendly, cost-effective, and scalable synthesis techniques is crucial not only for industrial upscaling but also for ensuring the long-term viability of MXene-based technologies. A shift toward green chemistry approaches, including milder etching solutions or electrochemical methods, can reduce environmental risks and production costs.

Equally critical is the ability to tailor MXene compositions and surface chemistries to target specific waterborne contaminants. The controlled engineering of surface terminations and elimination of inherent or process-induced defects will directly influence the performance of the membranes. Notably, MXenes such as $Ti_3C_2T_x$ lack in-plane porosity, and transport phenomena in stacked structures depend heavily on interlayer spacing. Creating uniformly porous MXene sheets remains a big challenge due to their multi-atomic-layered nature compared to single-atom-layer materials like graphene. Nonetheless, advances in nanofabrication and exfoliation techniques may soon enable the design of high-flux, selective, and stable porous MXene membranes.

Another key area for advancement lies in membrane fabrication. Techniques like interfacial polymerization, vacuum-assisted self-assembly, and layer-by-layer deposition need to be optimized for MXene integration. In parallel, the theoretical understanding of MXene behaviour during membrane formation and under operational conditions is still growing. In-depth studies using in situ techniques to track oxidation, fouling, and molecular transport in real time are essential to bridge this knowledge gap.

For successful deployment in practical systems, MXene-based membranes must also be tested under realistic operating conditions. Designing membranes in hollow fiber or tubular modules with high surface area-to-volume ratios will improve efficiency and space utilization. These designs must also be evaluated for mechanical strength, chemical resistance, and long-term operational stability, especially in complex water matrices and under varying pH, salinity, and pressure conditions.

Future research should further focus on exploring MXenes in energy-efficient desalination strategies. Sustained performance is frequently hindered by membrane fouling, especially biofouling. Anti-fouling strategies including the development of biofilm-resistant coatings, zwitterionic surfaces, or dynamic surface modifiers are crucial to extend membrane lifespan and reduce maintenance costs.

To fully realize the potential of MXenes, interdisciplinary collaboration will be essential merging materials science, chemical engineering, environmental science, and computational modeling. Machine learning and molecular dynamics simulations could offer predictive insights into structure function relationships, guiding the rational design of MXene-based membranes with tuneable performance metrics.

In summary, MXenes act as a bridge between material innovation and water treatment technology. Their integration into membrane systems offer a multifaceted solution to some of the most pressing challenges in clean water accessibility. While significant progress has been made over the past decade, the path ahead involves refining synthesis methods, engineering membrane architectures, and ensuring environmental compatibility. Through sustained research and innovation, MXenes have assured transition from the laboratory to impactful real-world applications, contributing meaningfully to global water sustainability.

Data availability

No data was used for the research described in the article.

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